NOAA Technical Memorandum NESDIS NGDC-51

DIGITAL ELEVATION MODELS OF CRESCENT CITY, CALIFORNIA: PROCEDURES, DATA SOURCES AND ANALYSIS

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Marine Geology and Geophysics Division
Boulder, Colorado
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Digital Elevation Models of Crescent City, California: Procedures, Data Sources and Analysis

1. Introduction

In June of 2010, the National Geophysical Data Center (NGDC), an office of the National Oceanic and Atmospheric Administration (NOAA), developed two bathymetric–topographic digital elevation models (DEMs) of Crescent City, California (Fig. 1). A 1/3 arc-second[1] DEM referenced to North American Vertical Datum of 1988 (NAVD 88) was carefully developed and evaluated. An NAVD 88 to mean high water (MHW) 1/3 arc-second conversion grid was then created to represent the relationship between NAVD 88 and MHW in the Crescent City region. A 1/3 arc-second MHW DEM, combining the NAVD 88 DEM and the conversion grid, will be used as input for the Method of Splitting Tsunami (MOST) model developed by the Pacific Marine Environmental Laboratory (PMEL) NOAA Center for Tsunami Research (http://nctr.pmel.noaa.gov/) to simulate tsunami generation, propagation and inundation. The NAVD 88 DEM was generated from diverse digital datasets in the region (grid boundary and sources shown in Fig. 3). The MHW DEM will be used for tsunami inundation modeling, as part of the tsunami forecast system Short-term Inundation Forecasting for Tsunamis (SIFT) currently being developed by PMEL for the NOAA Tsunami Warning Centers. This report provides a summary of the data sources and methodology used in developing the Crescent City DEMs.

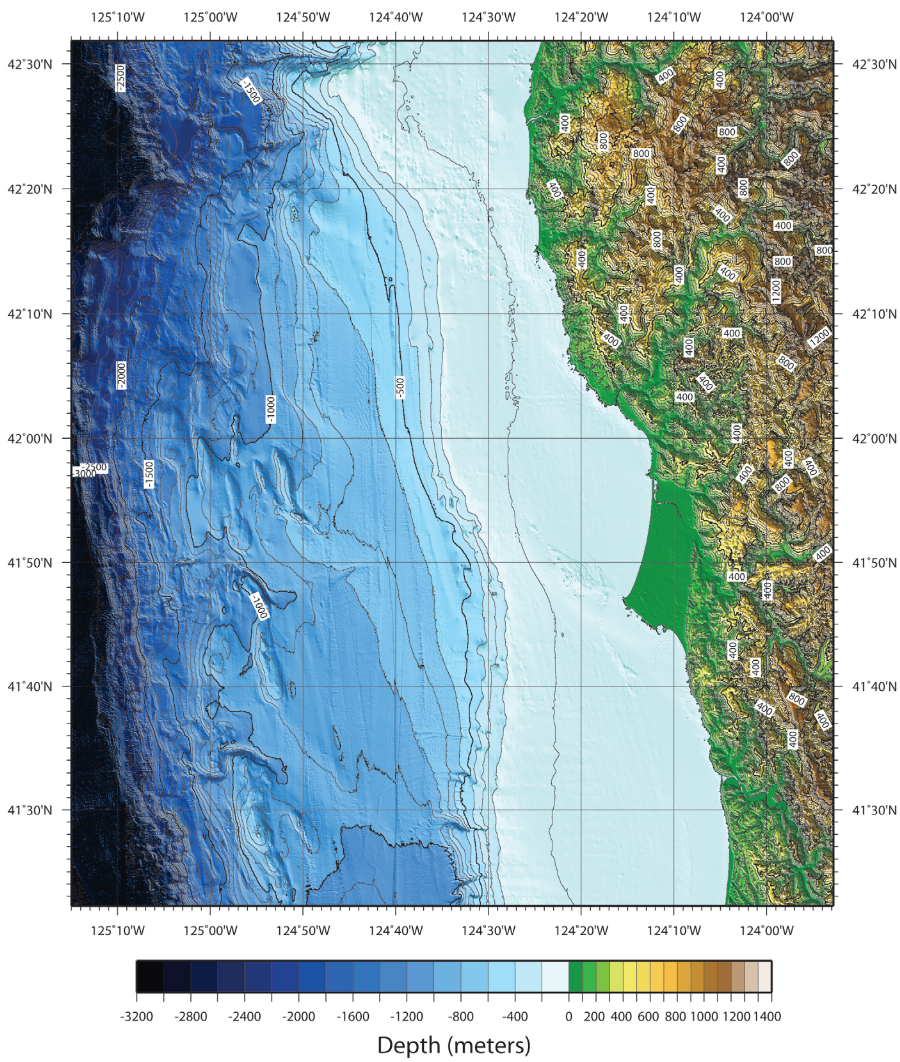

Figure 1. Shaded-relief image of the Crescent City NAVD 88 1/3 arc-second DEM. Contour interval is 100 meters. Image is in Mercator projection.

1. The Crescent City DEMs are built upon a grid of cells that are square in geographic coordinates (latitiude and longitude), however, the cells are not square when converted to projected coordinate systems such as UTM zones (in meters). At the latitude of Crescent City, California, (41°45'21"N, 124°12'6"W) 1/3 arc-second of latitude is equivalent to 10.28 meters; 1/3 arc-second of longitude equals 7.70 meters.

2. Study Area

The Crescent City DEMs extend from north of Gold Beach, Oregon to south of Klamath, California (Fig. 2). Crescent City is located in Northern California, 20 miles south of the Oregon border. The city covers an area approximately 1.6 square miles and has a population of 7,500 with the surrounding suburban population of 15,000.

Crescent City is considered to be more vulnerable to tsunamis than any other city along the West Coast of the United States, based on past events. Tsunami run-up events date back to late 1800's and early 1900's. The most devastating one that resonates in the memory of the local residents is the 1964 Gulf of Alaska tsunami, recording a maximum water height of 4.79 meters (http://www.ngdc.noaa.gov/hazard/hazards.shtml). Eleven people in Crescent City died from the tsunami.

Offshore bathymetry may play a role in amplifying tsunami wave heights at Crescent City. The Mendocino Escarpment, which is offshore from Crescent City, could provide channeling of tsunami energy towards the city. Crescent City Harbor also shows amplified wave frequencies around the 20-minute period, which could cause the amplified wave heights. Because of these reasons, Crescent City is considered a high priority site for tsunami inundation studies and the development of a forecast model (Arcas and Uslu, 2010).

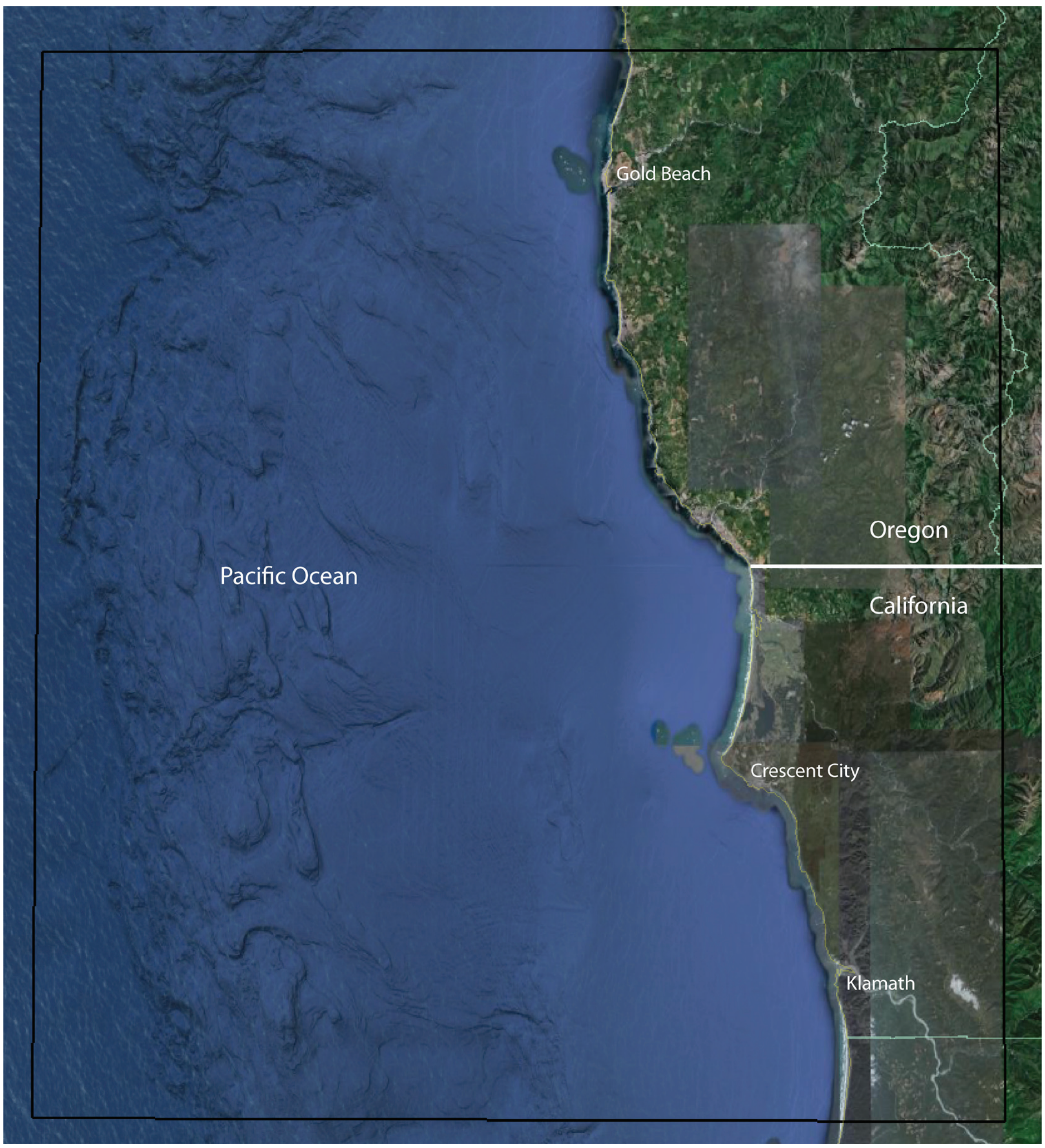

Figure 2. Google Earth imagery of the Crescent City DEM region. Black box denotes DEM boundary.

3. METHODOLOGY

The Crescent City NAVD 88 and MHW DEMs were constructed to meet PMEL specifications (Table 1), based on input requirements for the development of Reference Inundation Models (RIMs) and Standby Inundation Models (SIMs) (*V. Titov, pers. comm.*) in support of NOAA's Tsunami Warning Centers use of SIFT to provide real-time tsunami forecasts in an operational environment. The best available bathymetric and topographic digital data were obtained by NGDC and shifted to common horizontal and vertical datums: North American Datum of 1983[2] (NAD 83) and NAVD 88. The resulting NAVD 88 DEM was then transformed to MHW using a conversion grid for modeling of maximum flooding (see section 3.3.4). Data were gathered in an area slightly larger (~5%) than the DEM extents. This data "buffer" ensures that gridding occurs across rather than along the DEM boundaries to prevent edge effects. Data processing and evaluation, and DEM assembly and assessment are described in the following subsections.

Table 1. Specifications for the Crescent City DEMs.

Grid Area	Crescent City, California
Coverage Area	123.88º to 125.25º W; 41.42º to 42.53º N
Coordinate System	Geographic decimal degrees
Horizontal Datum	World Geodetic System of 1984 (WGS 84)
Vertical Datum	North American Vertical Datum of 1988 (NAVD 88) and Mean High Water (MHW)
Vertical Units	Meters
Cell Size	1/3 arc-second
Grid Format	ESRI Arc ASCII raster grid

2. The horizontal difference between the North American Datum of 1983 (NAD 83) and World Geodetic System of 1984 (WGS 84) geographic horizontal datums is approximately one meter across the contiguous U.S., which is significantly less than the cell size of the DEMs. Most GIS applications treat the two datums as identical, so do not actually transform data between them, and the error introduced by not converting between the datums is insignificant for our purposes. NAD 83 is restricted to North America, while WGS 84 is a global datum. As tsunamis may originate most anywhere around the world, tsunami modelers require a global datum, such as WGS 84 geographic, for their DEMs so that they can model the wave's passage across ocean basins. These DEMs are identified as having a WGS 84 geographic horizontal datum even though the underlying elevation data were typically transformed to NAD 83 geographic. At the scale of the DEMs, WGS 84 and NAD 83 geographic are identical and may be used interchangeably.

3.1 Data Sources and Processing

Shoreline, bathymetric, and topographic digital datasets (Fig. 3) were obtained from several U.S. federal, and state agencies including: NGDC; NOAA's National Ocean Service (NOS), Office of Coast Survey (OCS) and Coastal Services Center (CSC); California Department of Fish and Game (CDFG); California State University Monterey Bay (CSUMB); U.S. Army Corps of Engineers (USACE); and the U.S. Geological Survey (USGS). Safe Software's *FME* data translation tool package was used to shift datasets to NAD 83 geographic horizontal datum and to convert them into ESRI *ArcGIS* shapefiles or ASCII xyz files[3]. The shapefiles were then displayed with *ArcGIS* and the xyz files were displayed with Applied Imagery's *Quick Terrain Modeler* (*QT Modeler*) to assess data quality and manually edit datasets. Vertical datum transformations to NAVD 88 were accomplished using NOAA's *Vertical Datum* (*VDatum*) transformation tool. ESRI's online *World 2D* imagery was used to analyze and modify data. *QT Modeler* and Interactive Visualization System's *Fledermaus* software were used to evaluate processing and gridding techniques.

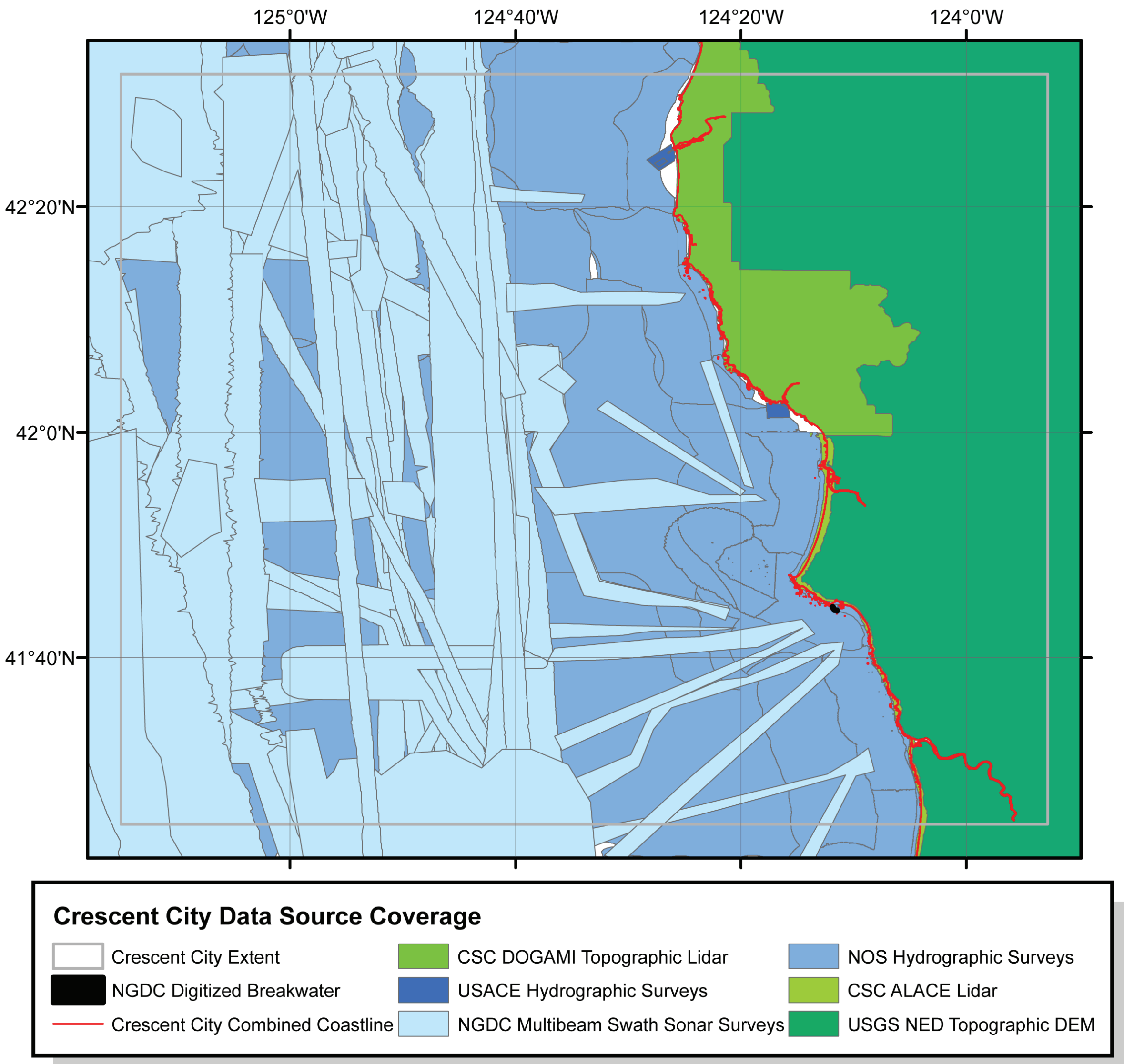

Figure 3. Source and coverage of datasets used in compiling the Crescent City NAVD 88 DEM.

3. *FME* uses the North American Datum Conversion Utility (NADCON; http://www.ngs.noaa.gov/TOOLS/Nadcon/Nadcon.shtml) developed by NOAA's National Geodetic Survey (NGS) to convert data from NAD 27 to NAD 83. NADCON is the U.S. Federal Standard for NAD 27 to NAD 83 datum transformations.

3.1.1 Shoreline

Coastline datasets of the Crescent City region were obtained from CDFG's Marine Region GIS Unit, NGDC, and the USGS (Table 2; Fig. 4). Coastlines from NOAA's OCS as Electronic Navigational Charts (ENCs)[4] were evaluated but were not used because they had lower spatial resolutions. These three datasets were used to develop a 'combined coastline' of the Crescent City region.

Table 2. Shoreline datasets used in developing the Crescent City NAVD 88 DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/ Coordinate System*	*Original Vertical Datum*	*URL*
CDFG	1996	Digitized 1:24,000 USGS quads	1:24,000	NAD 83 geographic	Mean high tide	http://www.dfg.ca.gov/marine/gis/
NGDC	2010	digitized vector shoreline		WGS 84 geographic	NAVD 88	
USGS	2002	vector shoreline		NAD 83 geographic	Mean high water	http://pubs.usgs.gov/of/2006/1251/#gis

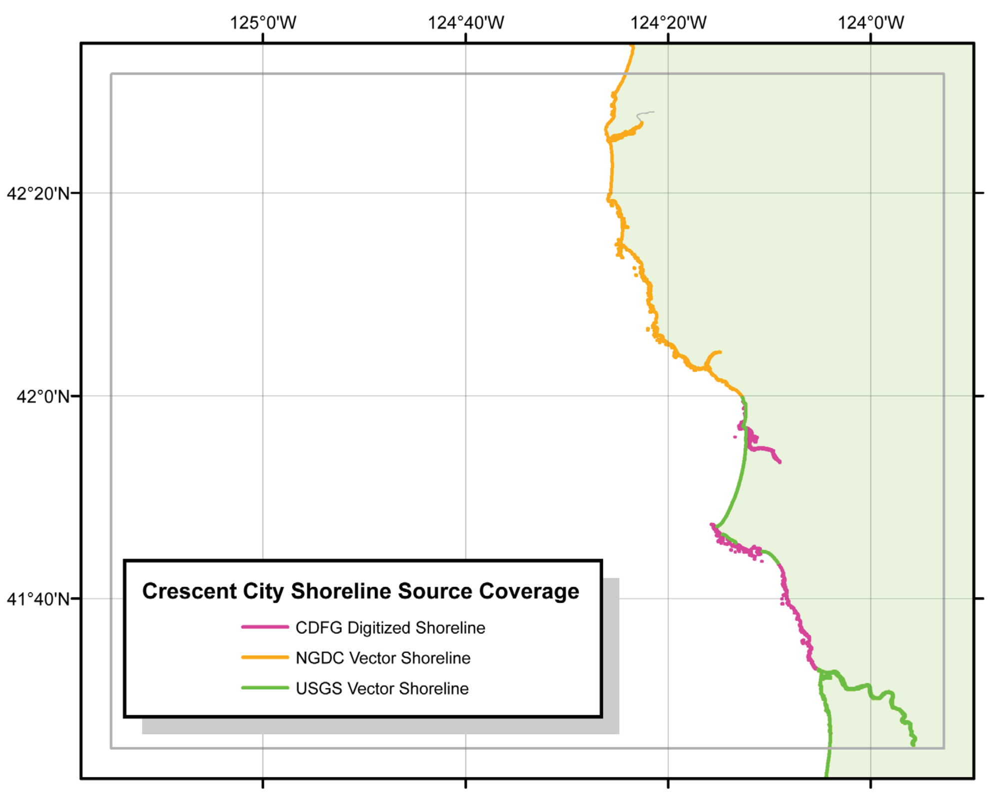

Figure 4. Digital coastline datasets used in developing a combined coastline of the Crescent City region. Land areas shown in green. Gray box denotes DEM boundary.

4. The Office of Coast Survey (OCS) produces NOAA Electronic Navigational Charts (NOAA ENC®) to support the marine transportation infrastructure and coastal management. NOAA ENC®s are in the International Hydrographic Office (IHO) S-57 international exchange format, comply with the IHO ENC Product Specification and are provided with incremental updates, which supply Notice to Mariners corrections and other critical changes. NOAA ENC®s are available for free download on the OCS web site. [Extracted from NOAA OCS web site: http://nauticalcharts.noaa.gov/mcd/enc/]

1) California Department of Fish and Game

The CDFG coastline was originally developed by the California State Land Commission from digitized USGS 7.5' quadrangles to define the mean high tide line and was subsequently rebuilt to reduce tolerances by the CDFG in 1996. The coastline was downloaded from the CDFG web site (see Table 2).

2) National Geophysical Data Center

The National Geophysical Data Center digitized a coastline from the California Oregon border to the northernmost DEM extent. The coastline was digitized with a vertical datum of NAVD 88 using primarily 2009 coastal lidar data for Southern Oregon, collected for the Oregon Department of Geology and Mineral Industries. ESRI's online *World 2D* imagery was used to verify the position of the coastline.

3) U.S. Geological Survey

The USGS compiled a vectorized shoreline of Northern California derived from 2002 lidar source data. The shoreline was created in response to the Nation's critical need of reliable shoreline data and was used to analyze shoreline change to determine vulnerabilities of the Northern California coast (USGS metadata; see Table 2). The vectorized shoreline was generated at mean high water.

The CDFG, NGDC, and USGS coastlines were merged together using *ArcCatalog* and used to create a combined coastline of the Crescent City region. The combined coastline was modified to include large offshore rocks and small inlets and rivers as shown on the larger-scale Raster Nautical Charts (RNCs) and clipped to 0.05 degrees larger than the DEM boundary. Smaller piers and docks were deleted from the coastline (Fig. 5). The coastline was further modified based on ESRI's *World 2D* imagery to reflect the most current coastal morphology.

Figure 5. Coastline in Crescent City Harbor (red line) shown with ESRI World 2D Imagery. Piers are not included in the coastline as water can flow beneath them, but large rocks and breakwaters were included as they are solid structures.

3.1.2 *Bathymetry*

Bathymetric datasets available for use in the compilation of the Crescent City DEMs include 30 NOS hydrographic surveys; 29 multibeam surveys retrieved from the NGDC multibeam database; and hydrographic surveys from USACE. (Table 3; Fig. 6).

Table 3. Bathymetric datasets used in compiling the Crescent City NAVD 88 DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/ Coordinate System*	*Original Vertical Datum*	*URL*
NGDC	1925 to 2008	NOS hydrographic survey soundings	Ranges from 5 meters to 1.2 kilometers (varies with scale of survey, depth, traffic and probability of obstructions)	NAD 1913, NAD 27, NAD 83, WGS 84 UTM Zone 10	MLLW (meters)	http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html
NGDC	1994 to 2009	Multibeam swath sonar surveys	Raw sonar files gridded to 1 arc-second	WGS 84 geographic	Assumed MSL (meters)	http://www.ngdc.noaa.gov/mgg/bathymetry/multibeam.html
USACE	2009 to 2010	Harbor survey	~varies	California and Oregon State Plane, NAD 83, feet	MLLW (feet)	http://www.nwp.usace.army.mil/op/nwh/xyzcoastal.asp

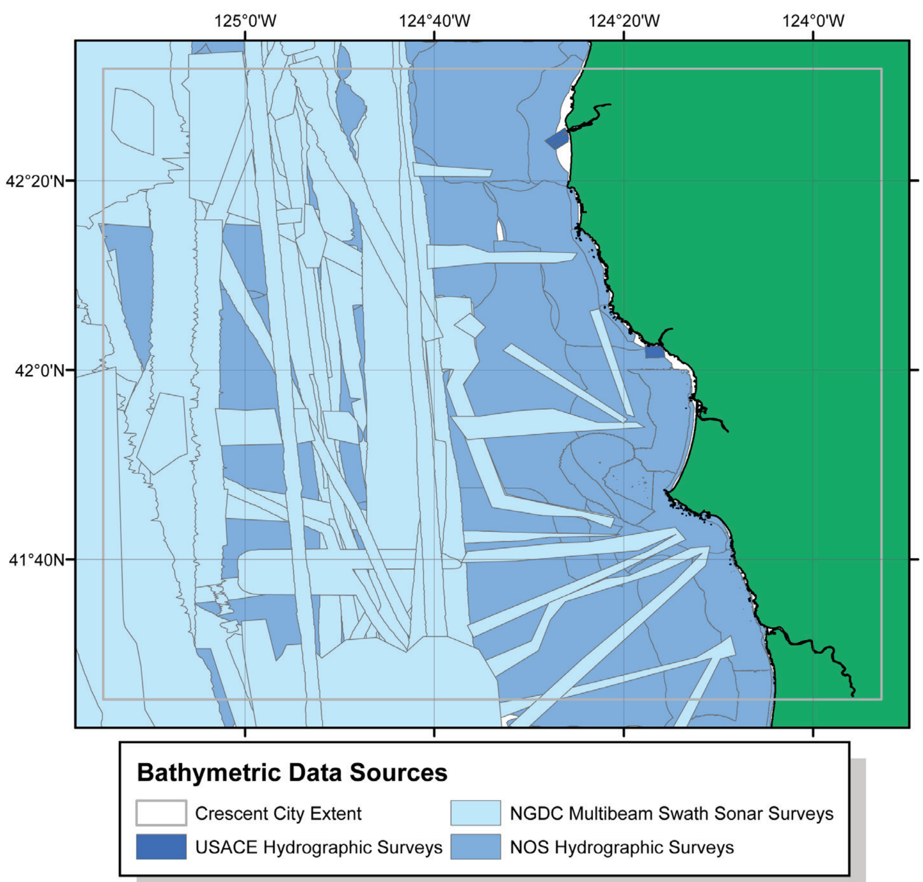

Figure 6. Source and coverage of bathymetric datasets used in compiling the Crescent City NAVD 88 DEM.

1) National Ocean Service hydrographic survey data

A total of 34 NOS hydrographic surveys conducted between 1925 and 2008 were available for use in developing the Crescent City DEMs. Surveys prior to 2000 were extracted as xyz files using *GEODAS*[5] from NGDC's online NOS hydrographic database with a buffer 0.05 degrees (~5%) larger than the Crescent City DEM area to support data interpolation along grid edges. The downloaded hydrographic survey data were vertically referenced to mean lower low water (MLLW) and horizontally referenced to NAD 83 geographic (Table 4; Fig. 7). The most recent surveys from 2008 and 2009 were provided to NGDC by NOS, retrieved from the NGDC multibeam database, or downloaded from CSUMB's web site. These surveys were provided in NAD 83 UTM Zone 10, and in either NAVD 88 or MLLW (see Table 4).

Data point spacing for the NOS surveys varied by scale. In general, small scale surveys had greater point spacing than large scale surveys. All NOS survey data were converted to NAVD 88 using the *VDatum* transformation tool (see Sec. 3.2.1). The data were then converted to shapefiles using *FME* software and displayed in ESRI *ArcMap* and reviewed for digitizing errors and edited as necessary. The surveys were also compared to other bathymetric datasets, the combined coastline, and NOS RNCs. Older surveys were clipped to remove soundings that have been superseded by more recent NOS surveys, USACE surveys, and multibeam data.

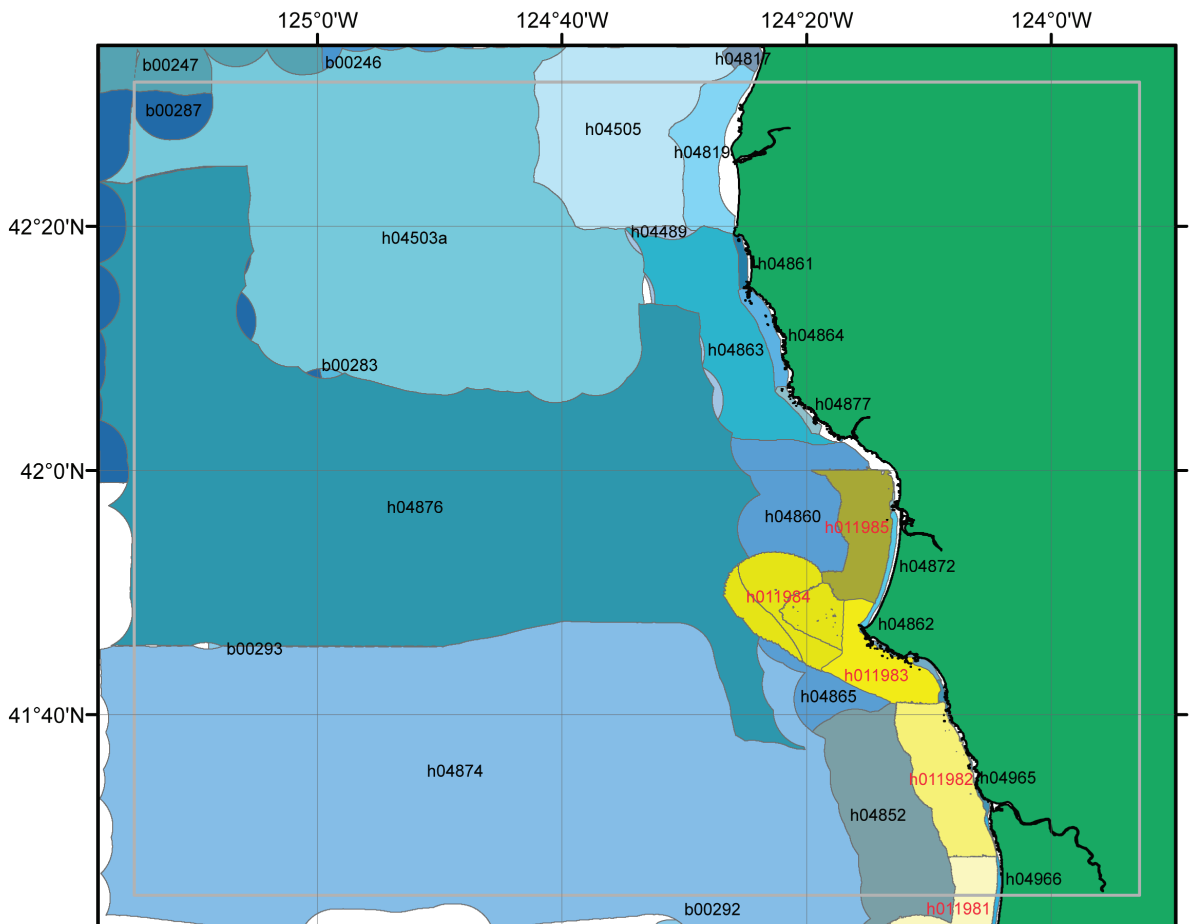

Figure 7. Digital NOS hydrographic survey coverage in the Crescent City region. Several older surveys were not used as they have been superseded by more recent surveys. NOS BAG files shaded in yellow with red text.

5. *GEODAS* uses the North American Datum Conversion Utility (NADCON; http://www.ngs.noaa.gov/TOOLS/Nadcon/Nadcon.shtml) developed by NOAA's National Geodetic Survey (NGS) to convert hydrographic survey data from NAD 27 to NAD 83. NADCON is the U.S. Federal Standard for NAD 27 to NAD 83 datum transformations.

Table 4. Digital NOS hydrographic surveys used in building the Crescent City NAVD 88 DEM.

NOS Survey ID	*Year of Survey*	*Survey Scale*	*Original Horizontal Datum*	*Original Vertical Datum*
B00132	1988	50,000	NAD 83 geographic	MLLW
B00246	1990	50,000	NAD 83 geographic	MLLW
B00247	1990	50,000	NAD 83 geographic	MLLW
B00283	1991	50,000	NAD 83 geographic	MLLW
B00287	1991	50,000	NAD 83 geographic	MLLW
B00292	1991	50,000	NAD 83 geographic	MLLW
B00293	1991	50,000	NAD 83 geographic	MLLW
B00298	1991	50,000	NAD 83 geographic	MLLW
F00562#	2008	5,000	UTM Zone 10 WGS 84	MLLW
H04489	1925	40,000	NAD 1913 geographic	MLLW
H04503a	1925	120,000	NAD 27 geographic	MLLW
H04505	1925	40,000	NAD 1913 geographic	MLLW
H04531	1925	120,000	NAD 1913 geographic	MLLW
H04817	1928	20,000	NAD 1913 geographic	MLLW
H04819	1928	20,000	NAD 1913 geographic	MLLW
H04852	1928	40,000	NAD 1913 geographic	MLLW
H04860	1928	40,000	NAD 1913 geographic	MLLW
H04861	1928	10,000	NAD 1913 geographic	MLLW
H04862	1928	20,000	NAD 1913 geographic	MLLW
H04863	1928	40,000	NAD 1913 geographic	MLLW
H04864	1928	20,000	NAD 1913 geographic	MLLW
H04865	1928	10,000	NAD 1913 geographic	MLLW
H04872	1928	20,000	NAD 1913 geographic	MLLW
H04874	1928	120,000	NAD 1913 geographic	MLLW
H04876	1928	120,000	NAD 1913 geographic	MLLW
H04877	1928-1934	5,000/10,000	NAD 27 geographic	MLLW
H04877a	1934	5,000	NAD 27 geographic	MLLW
H04965	1929	40,000	NAD 1913 geographic	MLLW
H04966	1929	20,000	NAD 1913 geographic	MLLW
H11981*	2008	2 m	UTM Zone 10 WGS 84	NAVD 88
H11982*	2008	2 m	UTM Zone 10 WGS 84	NAVD 88
H11983#	2008	40,000	UTM Zone 10 WGS 84	MLLW
H11984*	2008	2 m and 5 m	UTM Zone 10 WGS 84	NAVD 88
H11985*	2008	2 m	UTM Zone 10 WGS 84	NAVD 88

* Denotes NOS survey downloaded from CSUMB web site.
# Denotes NOS survey retrieved from NGDC's multibeam database.

2) Multibeam swath sonar surveys

Twenty-nine multibeam swath sonar surveys were available from the NGDC Multibeam Bathymetry database (Table 5). The data were referenced to WGS 84 geographic horizontal datum and were assumed to be in mean sea level (MSL) vertical datum. The data were gridded to extents approximately 5 percent larger than the DEM extents using *MB-System*[6] (http://www.ldeo.columbia.edu/res/pi/MB-System/) at 1 arc-second and viewed in *QT Modeler* for quality analysis. Editing was performed using *QT Modeler* and *ArcMap* to eliminate errors where survey data overlapped (Fig. 8). The grid was then converted to xyz format and the elevations were transformed from MSL to NAVD 88 using *VDatum* for use in the final gridding process.

Table 5. Multibeam swath sonar surveys used in compiling the Crescent City DEMs.

Survey ID	*Date*	*Institution*	*Ship*
AT07L14	2002	Woods Hole Oceanographic Institution (WHOI)	Ocean Alert
AT15L07	2006	WHOI	Atlantis
AT15L08	2006	WHOI	Atlantis
AT15L11	2006	WHOI	Atlantis
AVON08MV	1999	University of California, Scripps Institution of Oceanography (UC/SIO)	Coastal Surveyor
AVON09MV	1999	UC/SIO	Coastal Surveyor
CNTL04RR	2003	UC/SIO	Roger Revelle
DI-95-03	1995	NOAA	Ocean Alert
DRFT01RR	2001	UC/SIO	Roger Revelle
EW0209	2002	Columbia University, Lamont-Doherty Earth Observatory (CU/LDEO)	Roger Revelle
EW0407	2004	CU/LDEO	Maurice Ewing
EW9407	1994	CU/LDEO	Maurice Ewing
EW9408	1994	CU/LDEO	Maurice Ewing
EW9413	1994	CU/LDEO	Maurice Ewing
EW9414	1994	CU/LDEO	Maurice Ewing
EW9504	1995	CU/LDEO	Maurice Ewing
EW9505	1995	CU/LDEO	Melville
EW9905	1999	CU/LDEO	USCGC Healy
EX0902	2009	NOAA	Roger Revelle
EX0907	2009	NOAA	Melville
HLY03TA	2003	CU/LDEO	Nathaniel B. Palmer
LPRS02RR	2002	UC/SIO	Melville
LPRS03RR	2002	UC/SIO	Melville
LWAD99MV	1999	UC/SIO	Melville
NECR01RR	2000	UC/SIO	Roger Revelle
RB9702	1997	NOAA	Melville
SO108	1996	University of Kiel, Germany, GEOMAR Forshungzentrum (GEOMAR)	Sonne
Tecfluc	1998	Monterey Bay Aquarium Research Institute (MBARI)	Ocean Alert
Tran2sou	1998	MBARI	Ocean Alert

6. *MB-System* is an open source software package for the processing and display of bathymetry and backscatter imagery data derived from multibeam, interferometry, and sidescan sonars. The source code for *MB-System* is freely available (for free) by anonymous ftp (including "point and click" access through these web pages). A complete description is provided in web pages accessed through the web site. *MB-System* was originally developed at the Lamont-Doherty Earth Observatory of Columbia University (L-DEO) and is now a collaborative effort between the Monterey Bay Aquarium Research Institute (MBARI) and L-DEO. The National Science Foundation has provided the primary support for *MB-System* development since 1993. The Packard Foundation has provided significant support through MBARI since 1998. Additional support has derived from SeaBeam Instruments (1994-1997), NOAA (2002-2004), and others. URL: http://www.ldeo.columbia.edu/res/pi/MB-System/ from *MB-System* web site.]

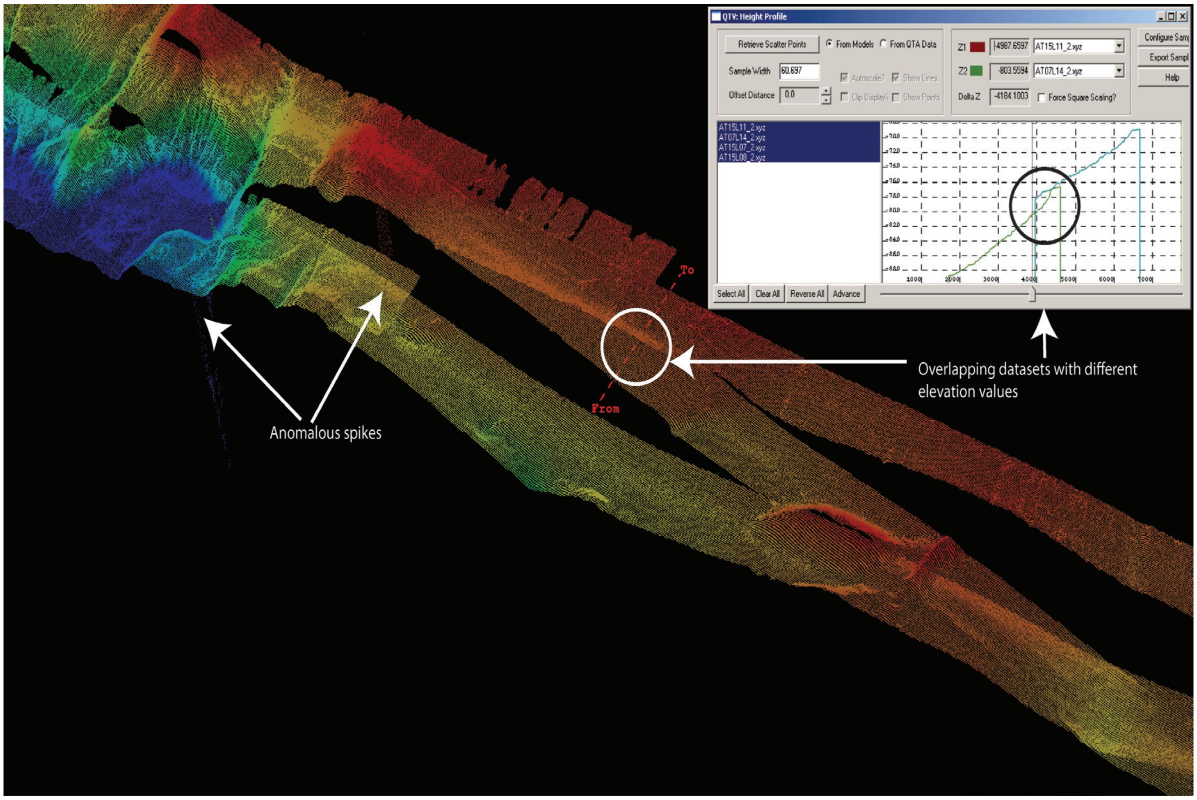

Figure 8. Examples of edits NGDC made to clean the multibeam swath sonar surveys. Anomalous spikes were deleted. Overlapping datasets were removed and a small buffer was used to allow smooth interpolation between datasets.

3) U.S. Army Corps of Engineers harbor survey

Six USACE hydrographic survey datasets, provided by Robert Yang from the San Francisco District, and eight surveys, downloaded from the Portland District were used in compiling the Crescent City DEM (Table 6; Fig. 9). These surveys were in xyz format, horizontally referenced to NAD 83 California State Plane and NAD 83 Oregon State Plane (feet), and vertically referenced to MLLW (feet). The data were transformed to NAD 83 geographic using *FME* and transformed to NAVD 88 using *VDatum*. The data were then converted to ESRI shapefiles for editing in *ArcMap.*

Table 6. USACE hydrographic surveys used in compiling the Crescent City DEMs.

Source	*Survey ID*	*Year*	*Original Vertical Datum*	*Original Horizontal Datum*	*Resolution*
Portland District	CHD_20090529	2009	MLLW, feet	Oregon State Plane NAD 83, feet	~30 meters
Portland District	CHT_20090831	2009	MLLW, feet	Oregon State Plane NAD 83, feet	~10 meters
Portland District	CHTA_20090613	2009	MLLW, feet	Oregon State Plane NAD 83, feet	30 meters in the transit line; transit lines ~150 meters apart
Portland District	CHTB_20090613	2009	MLLW, feet	Oregon State Plane NAD 83, feet	~15 meters
Portland District	RGA_20090529	2009	MLLW, feet	Oregon State Plane NAD 83, feet	30 meters in the transit line; transit lines ~150 meters apart
Portland District	RGB_20091104	2009	MLLW, feet	Oregon State Plane NAD 83, feet	~5 meters
Portland District	RGD_20090529_ DISPOSAL	2009	MLLW, feet	Oregon State Plane NAD 83, feet	30 meters in the transit line; transit lines ~60 meters apart
Portland District	ROG_20091104	2009	MLLW, feet	Oregon State Plane NAD 83, feet	~15 meters
San Francisco District	100203 Ma-rina longits-CLEAN Data-JD 034	2010	MLLW, feet	California State Plane NAD 83, feet	Less than a meter in the transit line; transit lines ~30 meters apart
San Francisco District	100203 Marinaxsec-CLEAN Data-JD 034	2010	MLLW, feet	California State Plane NAD 83, feet	Less than a meter in the transit line; transit lines ~15 meters apart
San Francisco District	100205 Marina longits-Clean Data-JD 036	2010	MLLW, feet	California State Plane NAD 83, feet	Less than a meter in the transit line; transit lines ~20 meters apart
San Francisco District	100205 Marina xsex-CLEAN Data-JD 036	2010	MLLW, feet	California State Plane NAD 83, feet	Less than a meter in the transit line; transit lines ~10 meters apart
San Francisco District	Crescent_City_ March2009_CON	2009	MLLW, feet	California State Plane NAD 83, feet	4 meters in the tran-sit line; transit lines ~30 meters apart
San Francisco District	Crescent_City_Ma-rina_March2009_ CON	2009	MLLW, feet	California State Plane NAD 83, feet	4 meters in the tran-sit line; transit lines ~30 meters apart

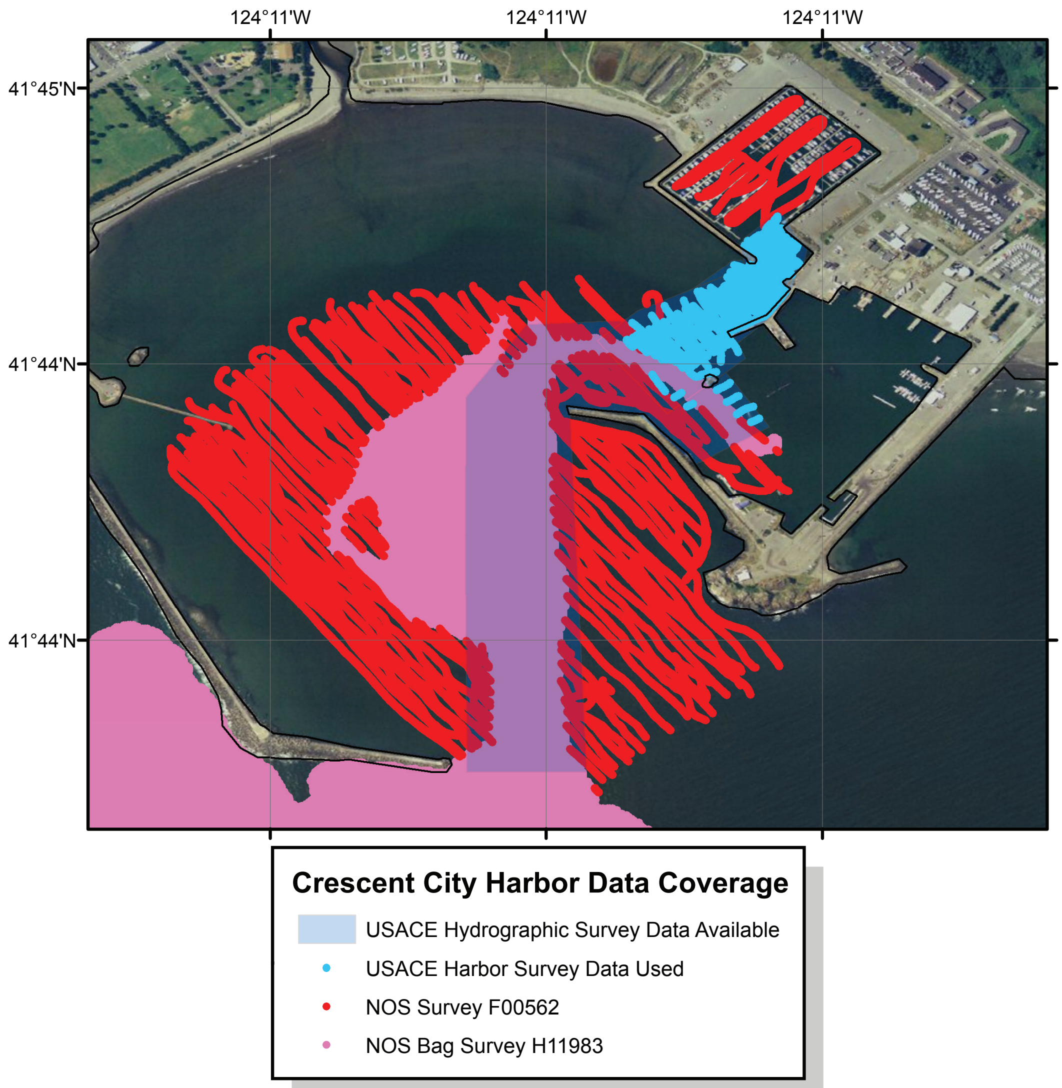

Figure 9. Source data coverage of Crescent City Harbor. The transparent polygon represents the USACE hydrographic data available for the harbor. A higher-resolution 2008 NOS BAG survey (pink) was available in the same region and was used instead.

3.1.3 Topography

Three topographic datasets in the Crescent City region, obtained from CSC and USGS were used to build the Crescent City NAVD 88 DEM (Table 7; Fig. 10). In addition, NGDC digitized elevation points along the Crescent City Harbor breakwater as it was not resolved completely in the other topographic datasets.

Table 7. Topographic datasets used in building the NAVD 88 Crescent City DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*	*URL*
CSC	2002	Lidar	3 meters	NAD 83 geographic	NAVD 88	http://csc.noaa.gov/digitalcoast/
CSC	2009	Lidar	10.24 points per m^2	NAD 83 geographic	NAVD 88	
NGDC	2010	Digitized elevations	1/3 arc-second	NAD 83 geographic	NAVD 88	
USGS	1999	NED DEM	1/3 arc-second	NAD 83 geographic	NAVD 88	http://ned.usgs.gov/

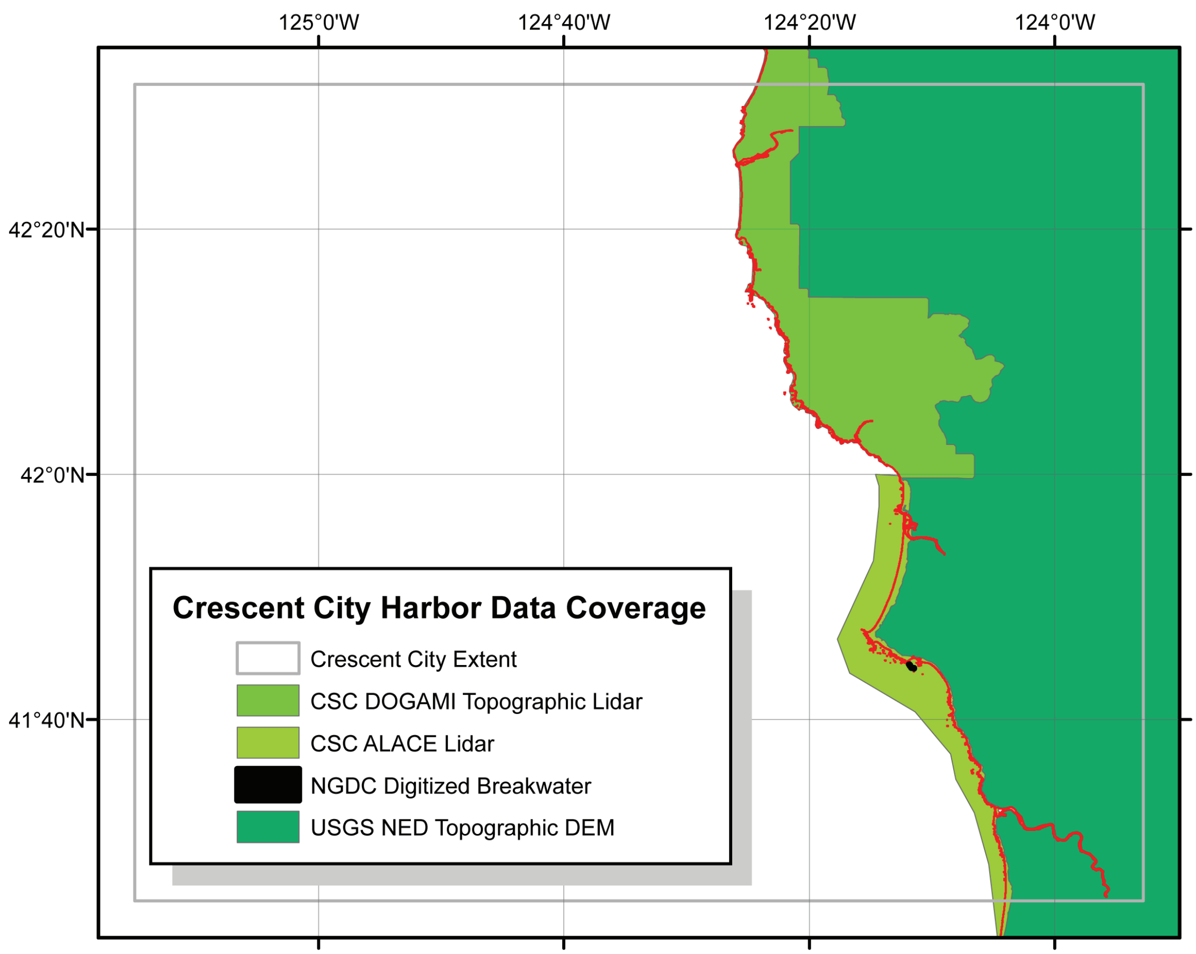

Figure 10. Source and coverage of topographic datasets used in compiling the Crescent City NAVD 88 DEM.

1) Coastal Services Center 2002 ALACE lidar

The 2002 NASA/USGS ALACE project lidar dataset was downloaded from the CSC web site. The lidar dataset was horizontally referenced to NAD 83 geographic and vertically referenced to NAVD 88. The data were transformed to MHW using *VDatum* (See Sec. 3.2.1). The elevations in the lidar dataset have a vertical accuracy of +/- 0.2 meters, although the dataset was not processed to bare-earth and contained vegetation and building values, as well as elevation values over open water. All values over water were clipped out of the dataset and only near-shore values were retained where there were no trees and minimal houses and shrubbery (Fig. 11).

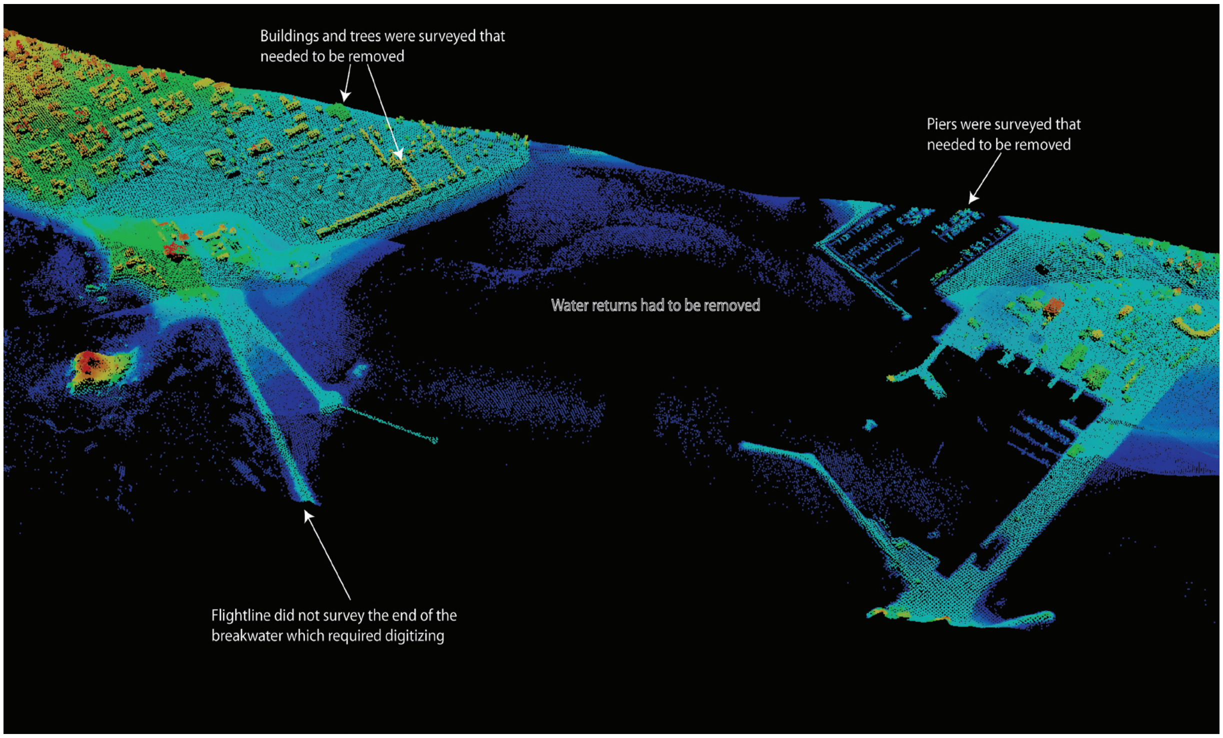

Figure 11. QT Modeler image of Crescent City showing examples of problems with the CSC lidar dataset. Part of the breakwater was not surveyed; buildings, trees, piers, and values over the open water all needed to be removed.

2) Coastal Services Center 2009 Oregon Department of Geology and Mineral Industries Lidar

Watershed Science, Inc. (WS) collected lidar data for DOGAMI of the southern Oregon coast. The data have an accuracy with a root mean square error (RMSE) of 0.4 meters, a 1-sigma absolute deviation of 0.14 meters, and a 2-sigma absolute deviation of 0.33 meters, and a data resolution of 10.24 points per m^2. The data were provided to NGDC by CSC in .las v. 1.1 format in NAD 83 and NAVD 88 datum (Geoid 09). NGDC classified the data to bare earth, converted it to xyz format, and clipped all elevation values that existed over the open ocean.

3) NGDC digitized features

In Crescent City Harbor, lidar data did not provide complete coverage of the breakwaters. Using the available lidar elevations from CSC as a reference, NGDC digitized a point shapefile to represent the elevations at 10 meters point spacing (Fig. 12). Generally, the elevation of the breakwater is ~4.3 meters at MLLW based on the USACE report "Monitoring of Dolos Armor Units at Crescent City, California" (Myrick and Melby, 2005).

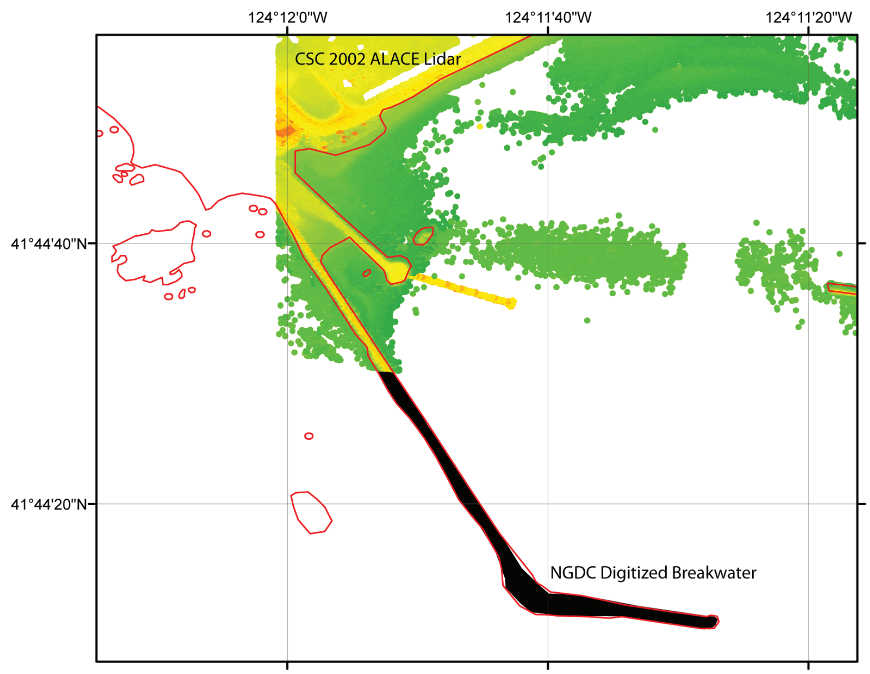

Figure 12. NGDC digitized breakwater. The CSC 2002 ALACE lidar data did not survey the end of the breakwater and so NGDC digitized the end of it based on the lidar data elevations and a USACE report description.

Several large off-shore rocks were not represented by any data but were documented in the RNCs and visible in satellite imagery. NGDC digitized the rocks according to the RNC elevation values. Rocks marked at the surface in the RNC were given an elevation value just above NAVD 88 zero elevation value.

Lake Earl, just north of Crescent City, has no bathymetry values. Based on readings from local kayakers and fishermen, the lake sits a little over 2 meters above sea level and usually no deeper than ~1.5 meters. These values have no vertical control. NGDC digitized the lake at 0.5 meters at NAVD 88 vertical datum in order to "flood" the lake in the MHW grid to represent more realistic lake depths.

4) U.S. Geological Survey NED 1/3 DEM

USGS National Elevation Dataset (NED) provides complete 1/3 arc-second coverage of the Crescent City region[7]. The dataset is available for download as raster DEMs in NAD 83 geographic horizontal datum and NAVD 88 vertical datum (meters). The bare-earth elevations have a vertical accuracy of +/- 7 to 15 meters depending on source data resolution (see the USGS Seamless web site for specific source information: http://seamless.usgs.gov). The dataset was derived from USGS quadrangle maps and aerial photographs based on topographic surveys.

The USGS NED 1/3 arc-second DEM data were downloaded from the USGS web site. The data were edited to remove anomalous elevation values over the water. *FME* was used to convert raster data to xyz format. A comparison of contour lines generated from the NED raster data (NAVD 88) to the USGS topographic quadrangles showed that the NED DEMs in the Crescent City region are in a mixed vertical datum of NAVD 88 inland and of MHW at the coast (see *Lim et al., 2009* for further details). To partially correct for this, elevations in this dataset that were below 2 meters were converted to 2 meters, which is roughly 0.3 meters larger than the difference between NAVD 88 and MHW in the Crescent City region. This prevented some coastal areas from inappropriately "flooding" with each tidal cycle in the MHW DEM.

7. The USGS National Elevation Dataset (NED) has been developed by merging the highest-resolution, best quality elevation data available across the United States into a seamless raster format. NED is the result of the maturation of the USGS effort to provide 1:24,000-scale Digital Elevation Model (DEM) data for the conterminous U.S. and 1:63,360-scale DEM data for Georgia. The dataset provides seamless coverage of the United States, HI, AK, and the island territories. NED has a consistent projection (Geographic), resolution (1 arc second), and elevation units (meters). The horizontal datum is NAD 83, except for AK, which is NAD 27. The vertical datum is NAVD 88, except for AK, which is NGVD29. NED is a living dataset that is updated bimonthly to incorporate the "best available" DEM data. As more 1/3 arc second (10 m) data covers the U.S., then this will also be a seamless dataset. [Extracted from USGS NED web site]

3.2 Establishing Common Datums

3.2.1 Vertical datum transformations

Datasets used in the compilation and evaluation of the Crescent City NAVD 88 DEM were originally referenced to a number of vertical datums including MLLW, MSL, and NAVD 88. All datasets were transformed to NAVD 88 using the *VDatum* transformation tool (http://vdatum.noaa.gov/). The tidal relationships at the Crescent City tide station (http://tidesandcurrents.noaa.gov/) are provided in Table 8.

1) **Bathymetric data**

   The NOS hydrographic surveys, multibeam swath sonar surveys, and USACE surveys were transformed from MLLW and MSL to NAVD 88 using *VDatum*.

2) **Topographic data**

   The topographic datasets were originally referenced to NAVD 88 requiring no vertical transformations.

Table 8. Relationship between NAVD 88 and other vertical datums at the Crescent City tide station (# 9419750).

Vertical datum	*Value*	*Difference to NAVD 88*
MHHW	2.095	1.975
MHW	1.900	1.783
MSL	1.130	1.013
MLW	0.380	0.263
NAVD 88	0.117	0.00
MLLW	0.00	-0.117

3.2.2 Horizontal datum transformations

Datasets used to compile the Crescent City NAVD 88 DEM were originally referenced to WGS 84 geographic, NAD 83 geographic, NAD 27 geographic, NAD 1913 geographic, NAD 83 UTM Zone 10 North, WGS 84 UTM Zone 10 North, NAD 83 California State Plane (feet), and NAD 83 Oregon State Plane (feet) horizontal datums. The relationships and transformational equations between the geographic horizontal datums are well established. Transformations to NAD 83 geographic were accomplished using *FME* software.

3.3 Digital Elevation Model Development

3.3.1 Verifying consistency between datasets

After horizontal and vertical transformations were applied, the resulting ESRI shapefiles were checked in ESRI *ArcMap* and *Quick Terrain Modeler* for inter-dataset consistency. Problems and errors were identified and resolved before proceeding with subsequent gridding steps. The evaluated and edited ESRI shapefiles were then converted to xyz files in preparation for gridding. Problems included:

- Inconsistent, overlapping topographic datasets. The lower resolution datasets were clipped to high-resolution datasets.
- Data values over the ocean in the NED DEMs, and the CSC lidar topographic datasets. These datasets required automated clipping to the combined coastline or were edited manually.
- Discrepancies in NED DEM vertical datum. NGDC assigned an NAVD 88 elevation value of 2.0 meters to cells below 2.0 meters.
- Digital, measured bathymetric values from NOS surveys date back over 70 years. More recent data, such as the multibeam surveys, differed from older NOS data by as much as 50 meters vertically. The older NOS survey data were excised where more recent bathymetric data exists.
- Returns from vegetation and buildings in lidar datasets. Data values were only retained where there were no trees and little vegetation and houses. Anomalous returns were manually edited to remove remaining anomalies where possible.
- The breakwater in Crescent City harbor is not well-represented in available elevation data. Limited lidar data in the region and a written description of the breakwaters were used to estimate a constant elevation surface for the breakwater.

3.3.2 Smoothing of bathymetric data

Older NOS hydrographic survey data are generally sparse at the resolution of the Crescent City DEMs in both deep water and in some areas close to shore. In order to reduce the effect of artifacts in the DEM due to these low resolution datasets, and to provide effective interpolation into the coastal zone, a 1 arc-second-cell size 'pre-surface' bathymetric grid in NAVD 88 vertical datum was generated using *GMT*[8], an NSF-funded software application designed to manipulate data for mapping purposes (http://gmt.soest.hawaii.edu/).

The older NOS hydrographic point data, in xyz format, were clipped to remove overlap with the newer NOS surveys, USACE data, and NGDC multibeam data. All of the bathymetric data were then combined with points extracted from the adjusted MHW coastline—to provide a buffer along the entire coastline. The coastline elevation values were set to negative one meter to ensure a bathymetric surface approaching zero relative to MHW in areas where bathymetric data are sparse or non-existent.

The point data were then median-averaged using the *GMT* tool 'blockmedian' to create a 1 arc-second grid 0.05 degrees (~5%) larger than the Crescent City DEM gridding region. The *GMT* tool 'surface' was then used to apply a tight spline tension to interpolate elevations for cells without data values. The netcdf grid created by 'surface' was converted into an ESRI Arc ASCII grid file, and clipped to the combined coastline (to eliminate data interpolation into land areas). The resulting surface was compared with original soundings to ensure grid accuracy. Figures 13-15 show histograms of the NOS, NGDC multibeam, and USACE surveys compared to the 1 arc-second pre-surfaced bathymetric grid. Differences cluster around zero with the multibeam data have the largest differences of -200 to +170 meters when compared to the bathymetric surface. Points with the largest differences are located along steep gradients of elevation (e.g., submarine canyons) where the high-resolution surveys may include over 100 points that are averaged to a single cell elevation value.

Some inconsistencies were identified while merging the bathymetric datasets due to the range in ages and resolutions of the NOS hydrographic surveys. In areas where more recent data were available, the older surveys were either edited or not used. The gridded bathymetric surface was then converted to an xyz file for use in building the NAVD 88 DEM.

8. GMT is an open source collection of ~60 tools for manipulating geographic and Cartesian data sets (including filtering, trend fitting, gridding, projecting, etc.) and producing Encapsulated PostScript File (EPS) illustrations ranging from simple x-y plots via contour maps to artificially illuminated surfaces and 3-D perspective views. GMT supports ~30 map projections and transformations and comes with support data such as GSHHS coastlines, rivers, and political boundaries. GMT is developed and maintained by Paul Wessel and Walter H. F. Smith with help from a global set of volunteers, and is supported by the National Science Foundation. It is released under the GNU General Public License. URL: http://gmt.soest.hawaii.edu/ [Extracted from GMT web site.]

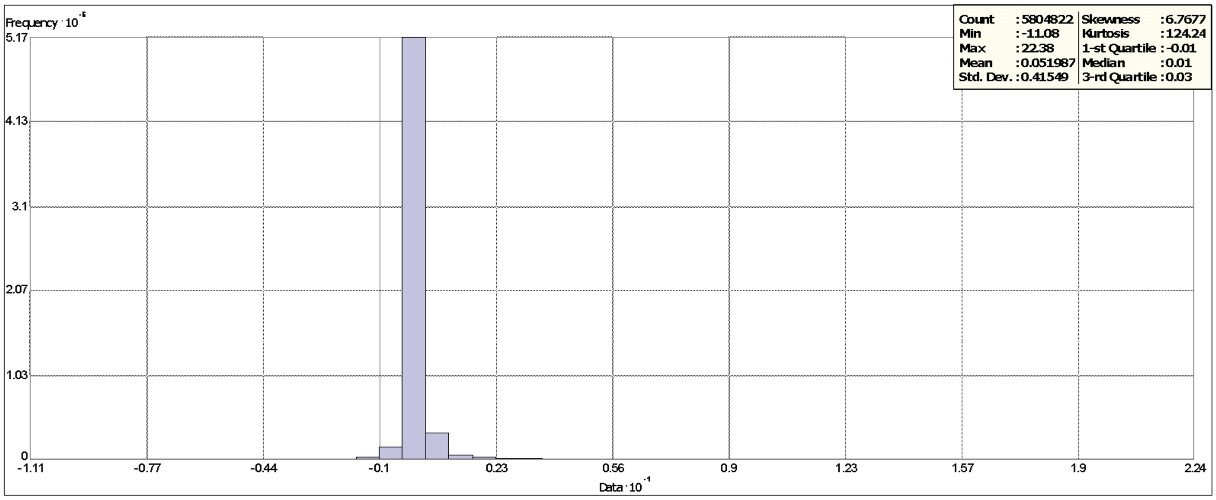

Figure 13. Histogram of the differences between NOS hydrographic survey H11983 and the 1 arc-second pre-surfaced bathymetric grid.

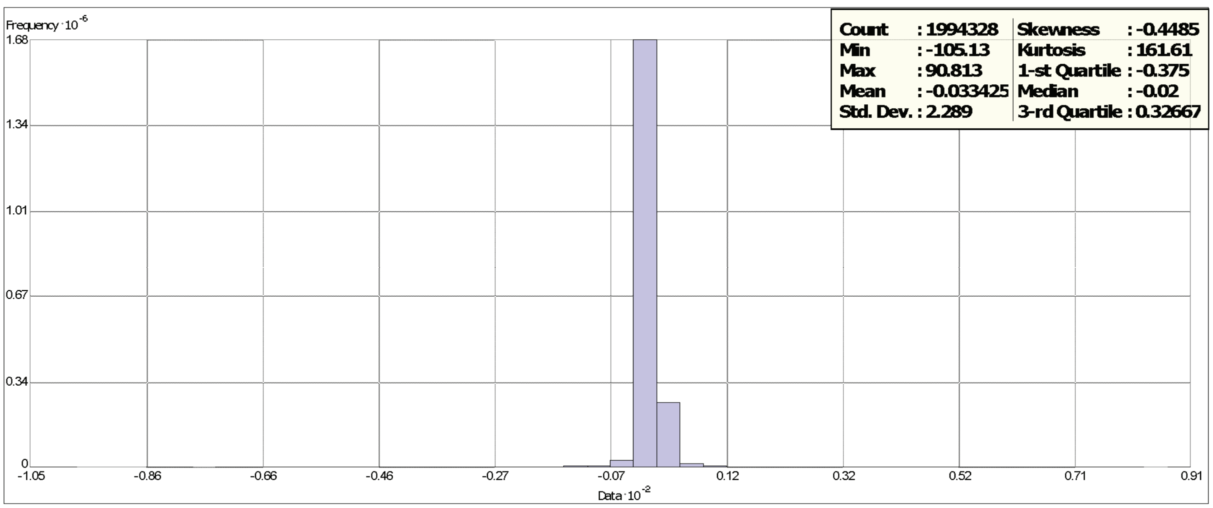

Figure 14. Histogram of the differences between all NGDC multibeam swath sonar surveys and the 1 arc-second pre-surfaced bathymetric grid.

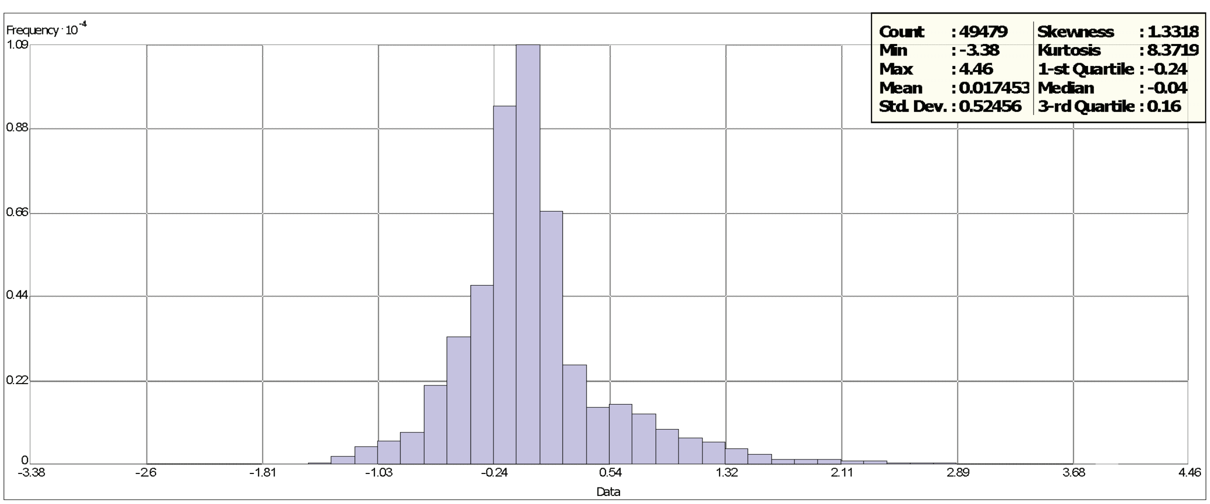

Figure 15. Histogram of the differences between all USACE hydrographic surveys and the 1 arc-second pre-surfaced bathymetric grid.

3.3.3 *Building the NAVD 88 DEM*

MB-System was used to create the 1/3 arc-second Crescent City NAVD 88 DEM. The *MB-System* tool 'mbgrid' was used to apply a tight spline tension to the xyz data, and interpolate values for cells without data. The data hierarchy used in the 'mbgrid' gridding algorithm, as relative gridding weights, is listed in Table 9. Greatest weight was given to the high-resolution topographic lidar, the high-resolution multibeam surveys, NOS BAG data, USACE hydrographic surveys, and the NGDC digitized features. Least weight was given to the pre-surfaced bathymetric grid, coastline, pre 2000 NOS hydrographic surveys, and the NED topographic DEM.

Table 9. Data hierarchy used to assign gridding weight in *MB-System*

Dataset	*Relative Gridding Weight*
Coastline	1
NGDC Bathymetric Surface	1
NOS - Pre 2000	1
USGS NED Topographic DEM	1
CSC ALACE Lidar	10
CSC DOGAMI Lidar	10
NGDC Digitized Features	10
NGDC Multibeam	10
NOS - Post 2000	10
USACE hydrographic soundings	10

3.3.4 *Building the MHW DEM*

The MHW DEM was created by adding an NAVD 88-to-MHW conversion grid to the NAVD 88 DEM.

1) Developing the conversion grid

Using extents slightly larger (~ 5 percent) than the DEM, an initial xyz file was created that contained the coordinates of the four bounding vertices and midpoint of the larger extents. The elevation value at each of the points was set to zero. The *GMT* tool 'surface' applied a tension spline to interpolate cell values making a zero-value 3 arc-second grid. This zero-value grid was then converted to an intermediate xyz file using the *GMT* tool 'grd2xyz'.

Conversion values from NAVD 88 to MHW at each xyz point were generated using *VDatum*. Null values were removed and a converted xyz file was created by clipping the data to the combined coastline using *FME*. The converted xyz file was then interpolated with the *GMT* tool 'surface' to create the 1/3 arc-second 'NAVD 88 to MHW' conversion grid with the extents of the NAVD 88 DEM (Fig. 16).

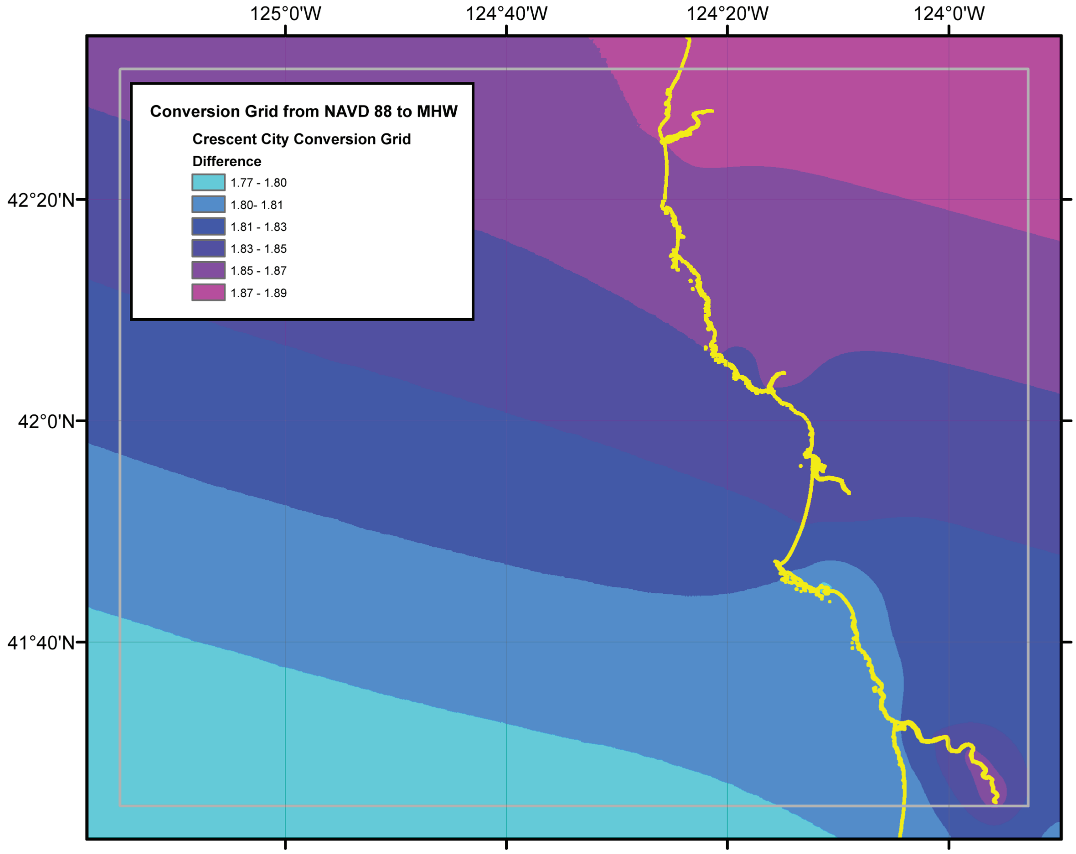

Figure 16. Image of the NAVD 88 to MHW conversion grid used to generate the MHW DEM. Coastline in yellow. Gray box denotes DEM boundary.

2) Assessing the accuracy of the conversion grid

The NAVD 88-to-MHW conversion grid was assessed using the NOS survey data. For testing of this methodology, the NOS hydrographic survey data were transformed from MLLW to NAVD 88 using *VDatum*. Shapefiles of the resultant xyz files were created and null values removed using *FME*. The shapefiles were then merged to create a single shapefile of all NOS surveys with a vertical datum of NAVD 88. A second shapefile of NOS data were created with a vertical datum of MHW using the same method. Elevation differences between the MHW and NAVD 88 shapefiles were computed after performing a spatial join in *ArcGIS*.

To verify the conversion grid methodology, the difference shapefile created using *ArcGIS* was converted to xyz format using *FME*. The CrossCheck module in *Fledermaus* was used to evaluate the performance of the 1/3 arc-second conversion grid by comparing the 'NAVD 88-to-MHW' grid to the difference xyz file. The *Fledermaus* results indicated agreement to approximately +/- 0.0003 meters with a mean difference of 0.000014 meters. The *Fledermaus* results were then converted to shapefile format using *FME* to visualize the comparison and to produce a histogram of the variations in *ArcGIS* (Fig. 17).

Errors in the vertical datum conversion method reside for the most part in the NAVD 88-to-MHW conversion grid; most topographic data are already in NAVD 88. Errors in the source datasets require rebuilding only the NAVD 88 DEM.

3) Creating the MHW DEM

Once the NAVD 88 DEM was complete and assessed for errors, the conversion grid was added to it using *ArcCatalog*. The resulting MHW DEM was reviewed and assessed using RNCs, USGS topographic maps, and ESRI *World 2D* imagery. Problems encountered were determined to reside in source datasets, which were corrected before building a new NAVD 88 DEM.

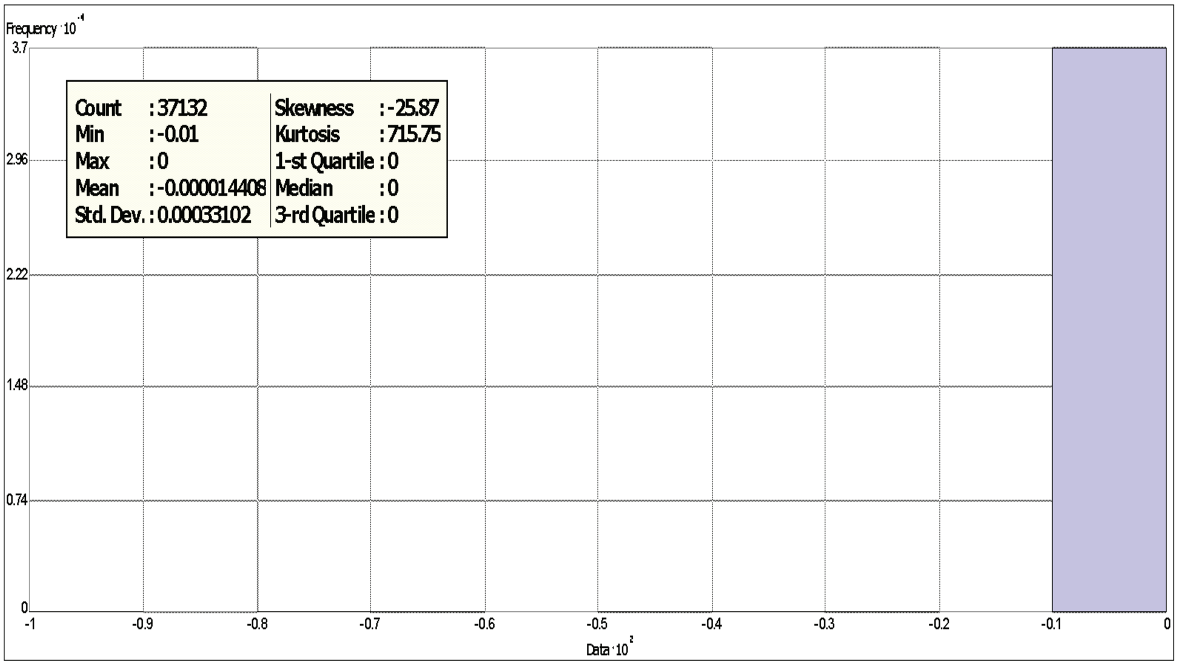

Figure 17. Histogram of the differences between the conversion grid and xyz difference files using NOS hydrographic survey data.

3.4 Quality Assessment of the DEMs

3.4.1 Horizontal accuracy

The horizontal accuracy of topographic and bathymetric features in the Crescent City DEMs is dependent upon DEM cell size and source datasets. Topographic features have an estimated horizontal accuracy of 10 meters: gridded CSC and USACE lidar data have an accuracy of approximately 1 meter and NED DEM data are accurate to approximately 10 meters. Bathymetric features are resolved only to within a few tens of meters in deep-water areas. Shallow, near-coastal regions, rivers, and harbor surveys have an accuracy approaching that of sub-aerial topographic features. Positional accuracy is limited by the sparseness of deep-water soundings and potentially large positional uncertainty of pre-satellite navigated (e.g., GPS) NOS hydrographic surveys.

3.4.2 Vertical accuracy

Vertical accuracy of elevation values in the Crescent City DEMs is also dependent upon the source datasets contributing to DEM cell values. Topographic data have an estimated vertical accuracy between 0.1 meters for bare-earth lidar data and 7 meters for NED DEMs. Bathymetric values have an estimated accuracy between 0.1 meters and 5% of water depth. Those values were derived from the wide range of sounding measurements from the early 20th century to recent, GPS-navigated multibeam swath sonar survey. Gridding interpolation to determine bathymetric values between sparse, poorly located NOS soundings degrades the vertical accuracy of elevations in deep water.

3.4.3 Slope map and 3-D perspectives

ESRI *ArcCatalog* was used to generate a slope grid from the Crescent City NAVD 88 DEM to allow for visual inspection and identification of artificial slopes along boundaries between datasets (Fig. 18). The DEM was transformed to NAD 83 UTM Zone 10 North coordinates (horizontal units in meters) in *ArcCatalog* for derivation of the slope grid; equivalent horizontal and vertical units are required for effective slope analysis. Analysis of preliminary grids using *QT Modeler* and *Fledermaus* revealed suspect data points, which were corrected before recompiling the DEM. Figure 1 shows a color image of the 1/3 arc-second Crescent City NAVD 88 DEM in its final version. Figure 19 shows a perspective rendering of the final NAVD 88 DEM. Figure 20 shows a data contribution plot of the Cresent City DEMs.

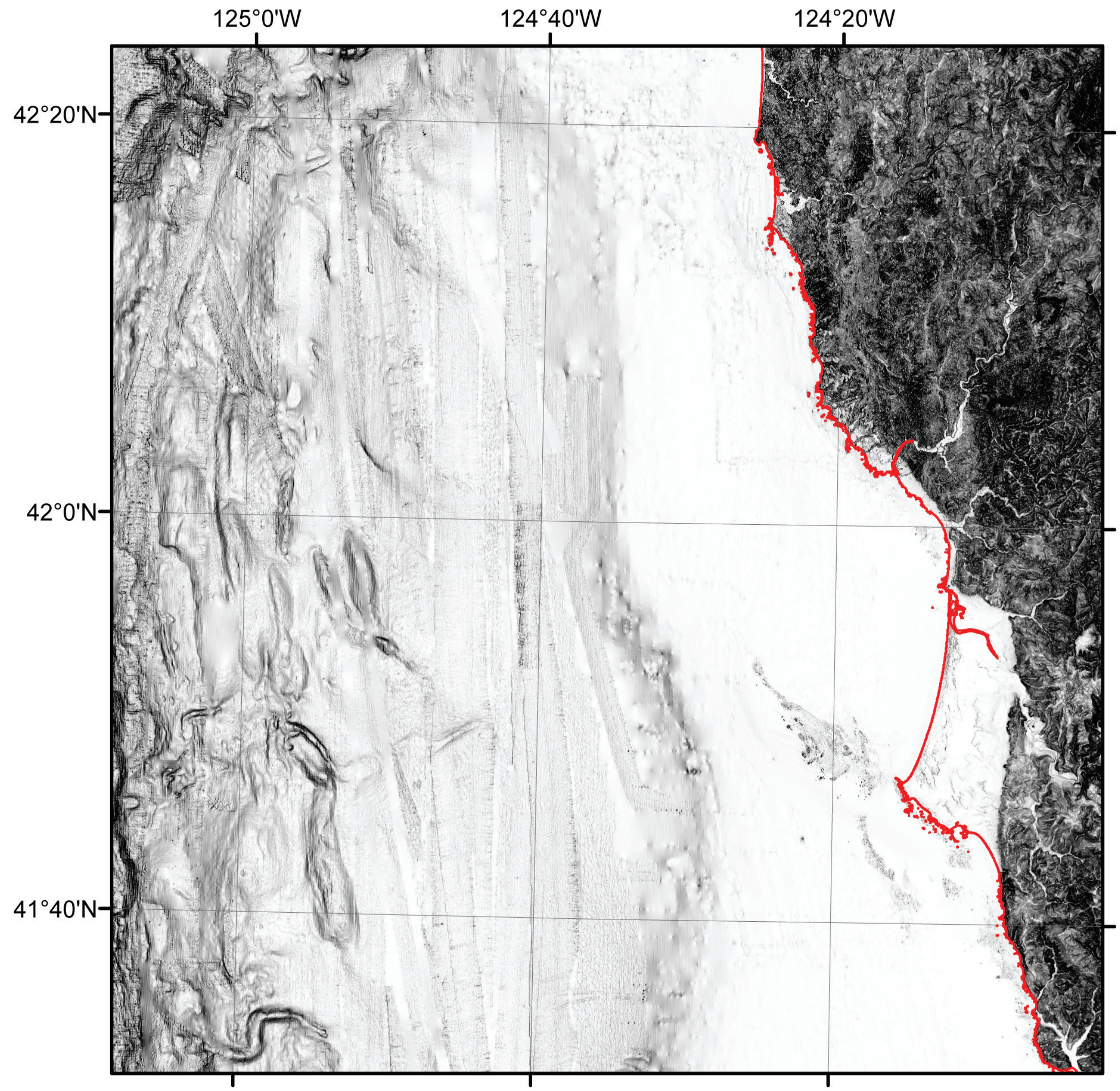

Figure 18. Slope map of the Crescent City NAVD 88 DEM. Flat-lying slopes are shown in white; dark shading denotes steep slopes; combined coastline indicated in red.

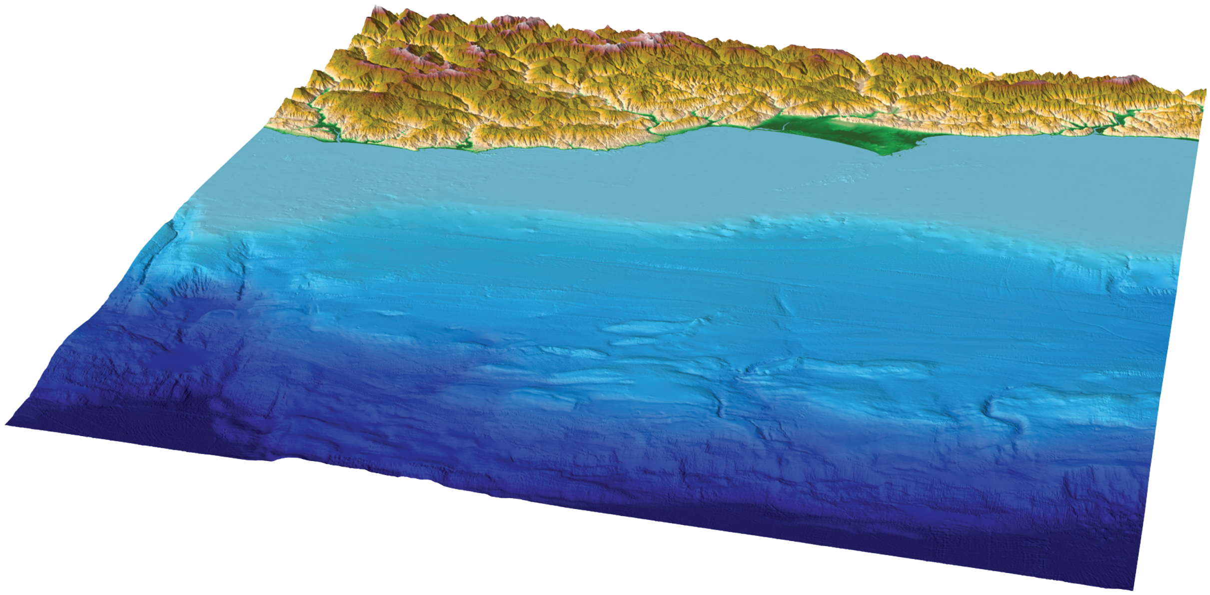

Figure 19. Perspective view from the west of the 1/3 arc-second Crescent City NAVD 88 DEM. Vertical exaggeration–times 2.

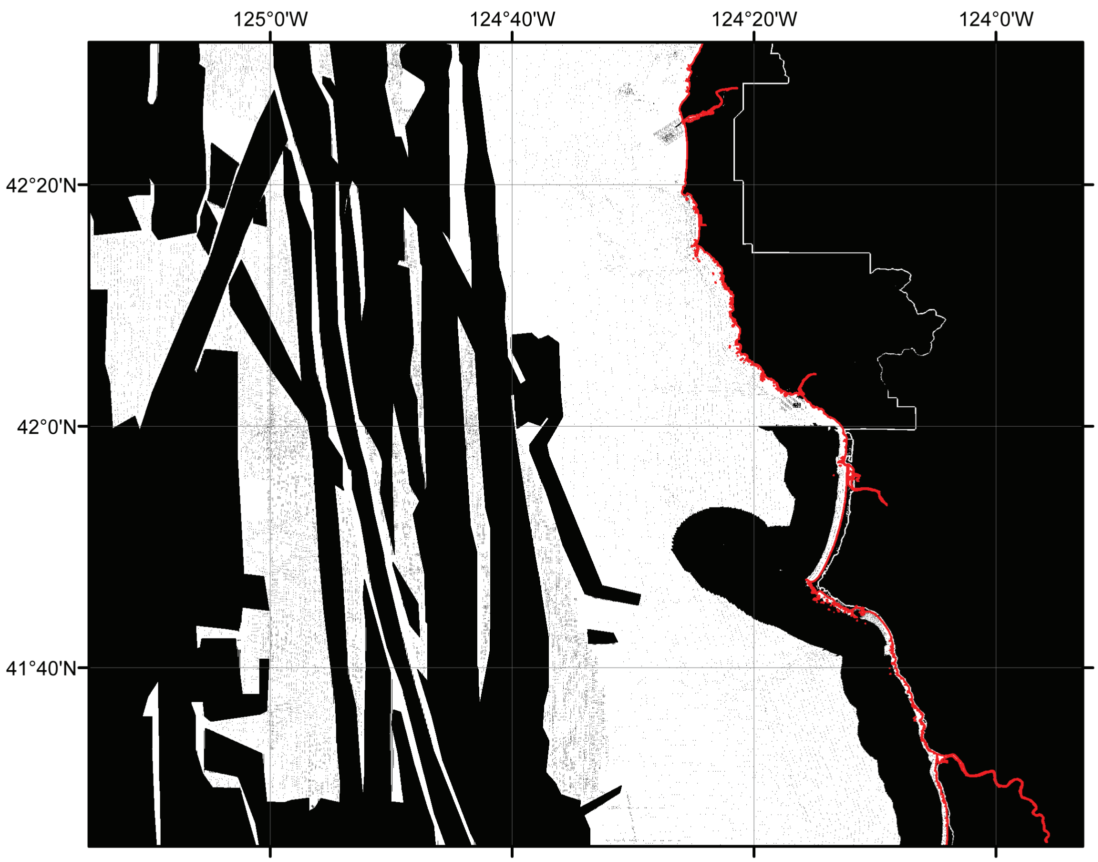

Figure 20. Data contribution plot of the Crescent City NAVD 88 DEM. Black depicts DEM cells constrained by source data; white depicts cells with elevation values derived from interpolation. Due to the scale of the image, sparse soundings may not be visible in the graphic. Coastline is shown in red.

3.4.4 *Comparison with National Geodetic Survey geodetic monuments*

The elevations of 776 geodetic monuments were extracted from the NOAA NGS web site (http://www.ngs.noaa.gov/) in shapefile format (see Fig. 21 for monument locations). Only 658 monuments with conditions noted as ‘GOOD’ or ‘MONUMENTED’ were included in the analysis. Shapefile attributes give positions in NAD 83 geographic (typically sub-mm accuracy) and elevations in NAVD 88 (in meters). Elevations were compared to the Crescent City NAVD 88 DEM (Fig. 22). Differences between the DEM and the monument elevations range from -162.88 to 133.58 meters with an outlier of 901.11 meters difference. The majority are within several meters. Large differences in elevations occurred where monuments are located on road cuts, on the top of buildings, or have conversion errors evident on the NGS data sheet (e.g., feet instead of meters).

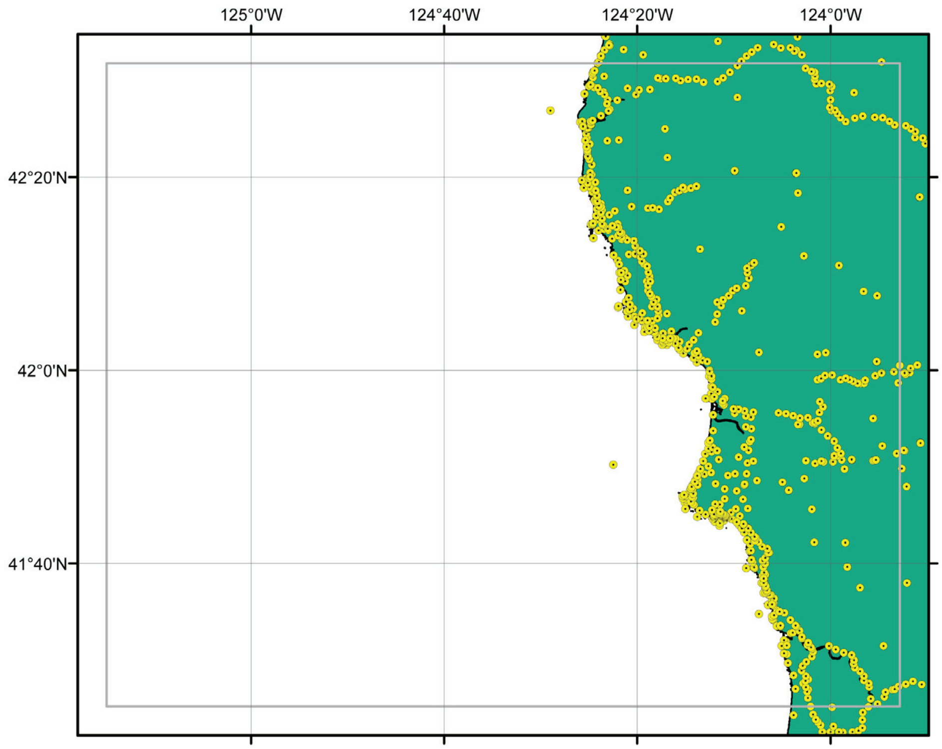

Figure 21. Location of NGS geodetic monuments, shown as yellow circles, in the Crescent City region.

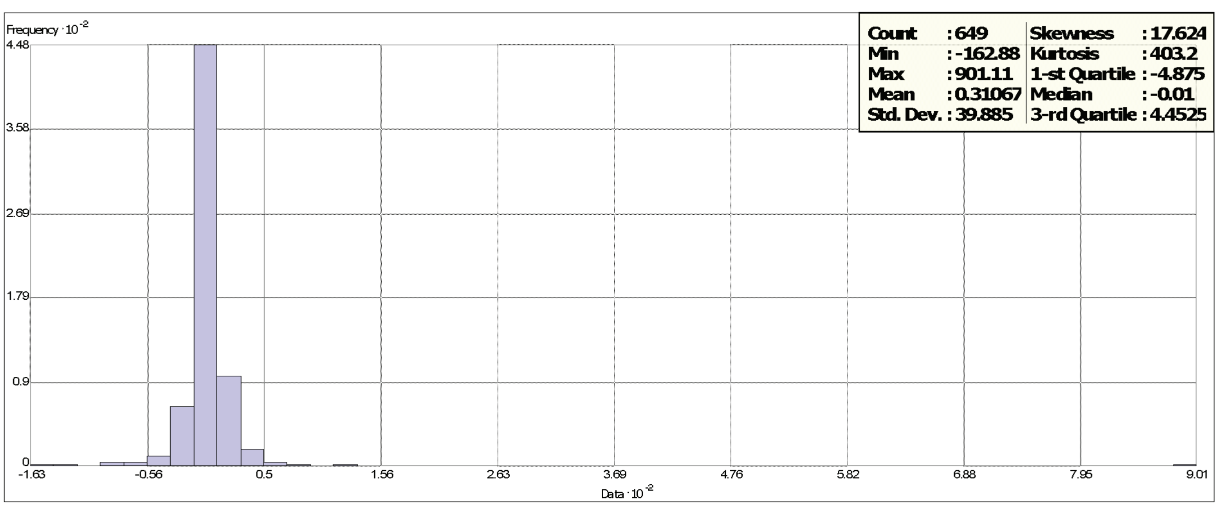

Figure 22. Histogram of the differences between NGS geodetic monument elevations and the Crescent City NAVD 88 DEM.

3.4.5 NAVD 88 DEM comparison with source data files

To ensure grid accuracy, the Crescent City NAVD 88 DEM was compared to source data files. Select bathymetric data and topographic data files were compared to the Crescent City NAVD 88 DEM using *Fledermaus*, *FME* and *ArcMap*.

A histogram of the differences between data points from the CSC DOGAMI topographic lidar data DEM and the Crescent City NAVD 88 DEM is shown in Figure 23. Differences cluster around zero. The major differences in elevations in DOGAMI lidar data points with the grid (-23.53 meters and +22.20 meters) are located in regions of steep slopes, where several points are averaged to obtain a single elevation value.

A random selection of CSC 2002 ALACE topographic lidar points were compared to the Crescent City NAVD 88 DEM (Fig. 24; a random selection was used to represent the overall survey as there were too many points to statistically compare with current processing methods). The histogram shows the differences in elevations are clustered around zero and the majority are within ± 1 meter. The largest differences are due to elevation values from trees that are average in the same cell with elevation values with no trees.

Comparison of all the USACE hydrographic survey data and the Crescent City NAVD 88 DEM are shown in Figure 25. The histogram shows the differences in elevations are clustered around zero with the elevation differences ranging from -9.68 to +2.18. The large negative differences occur along the edge of the breakwater where points fall into cells with topographic values.

A random selection of the NGDC multibeam swath sonar surveys were compared with the Crescent City NAVD 88 DEM. The histogram shows the differences in elevations range from -71.25 to +68.57 meters (Fig. 26). The largest differences are due to steep canyon slopes, where several points are averaged to obtain a single elevation value.

Comparison with NOS hydrographic surveys and the Crescent City NAVD 88 DEM are shown in Figure 27. The histogram shows the differences in elevations are clustered around zero with the elevation differences ranging from -32.85 to 58.83 meters.

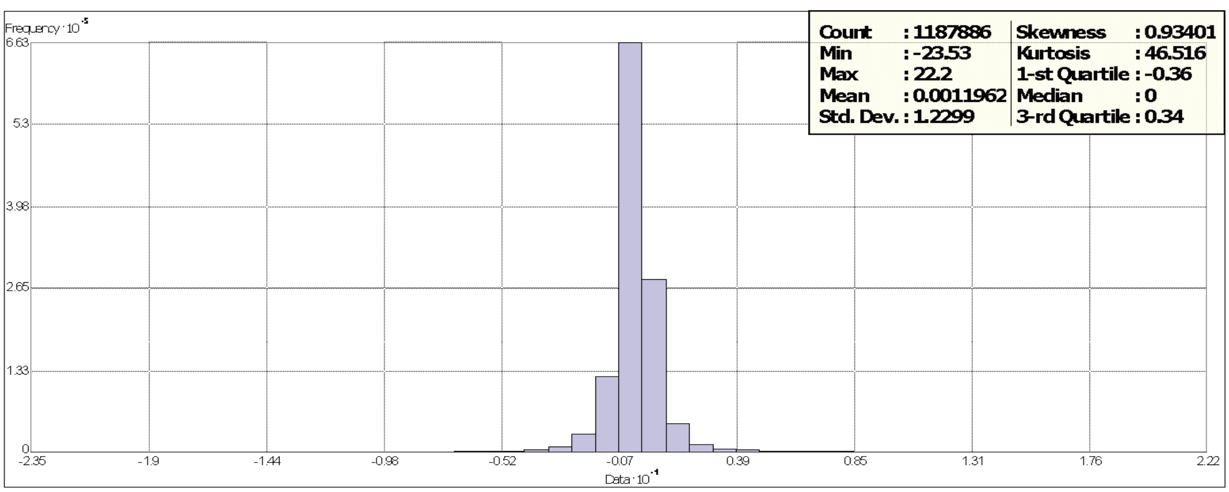

Figure 23. Histogram of the differences between select DOGAMI topographic lidar data points and the Crescent City NAVD 88 DEM.

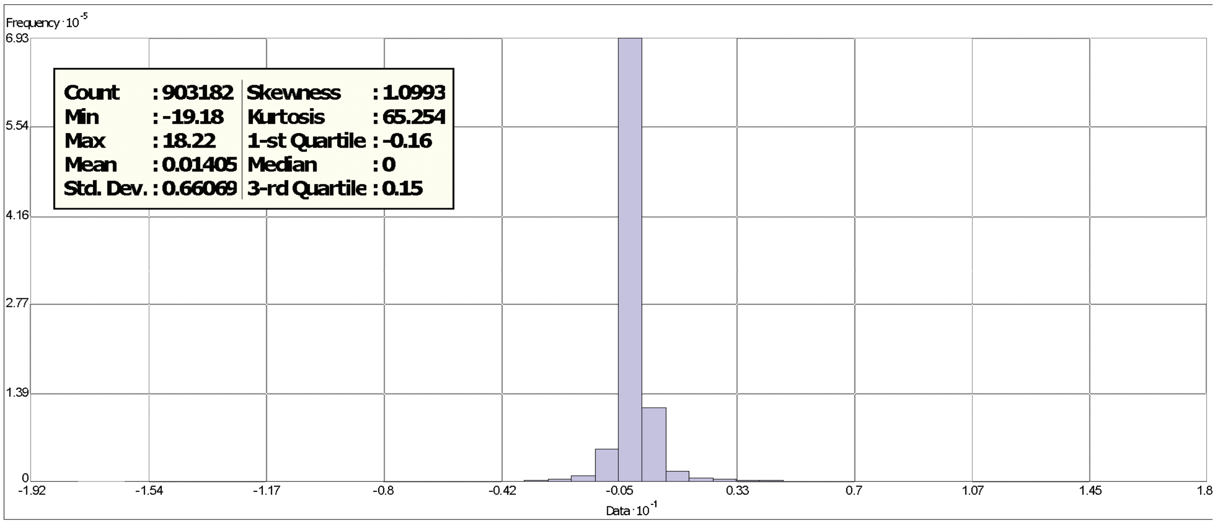

Figure 24. Histogram of the differences between select CSC ALACE topographic lidar data points and the Crescent City NAVD 88 DEM.

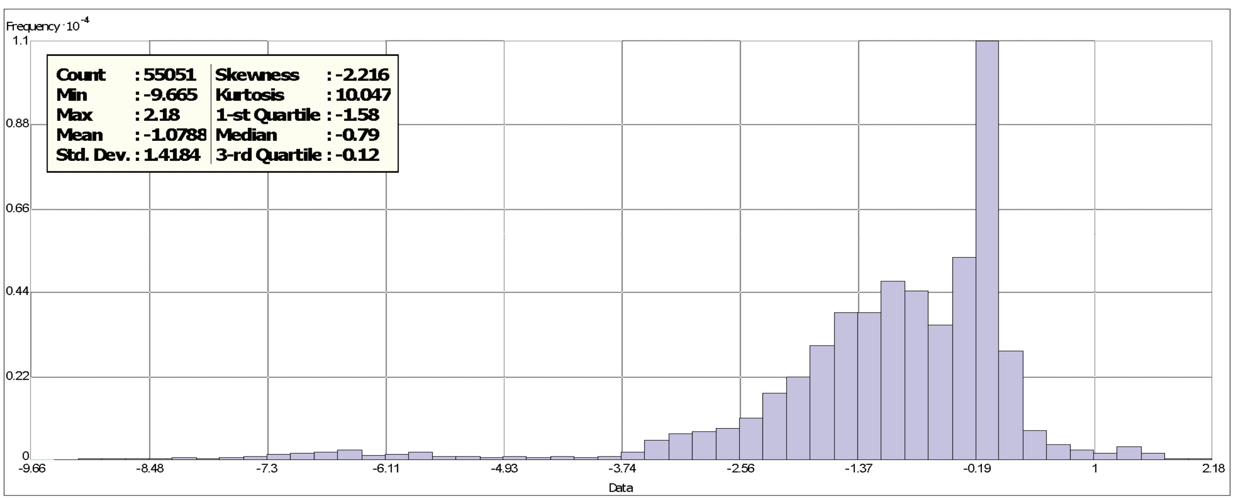

Figure 25. Histogram of the differences between USACE hydrographic data points and the Crescent City NAVD 88 DEM.

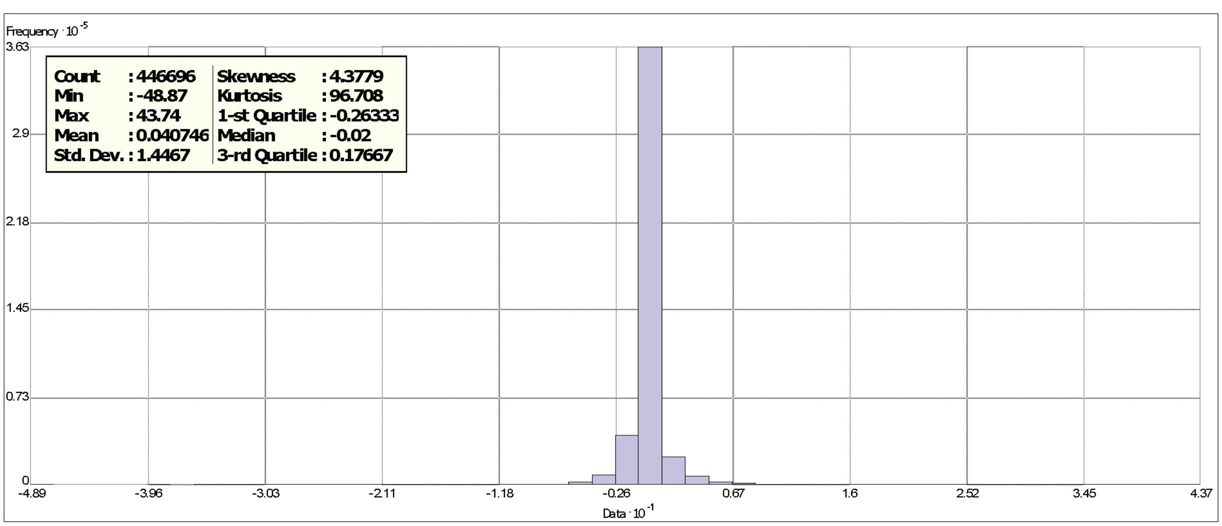

Figure 26. Histogram of the differences between select NGDC swath sonar multibeam data points and the Crescent City NAVD 88 DEM.

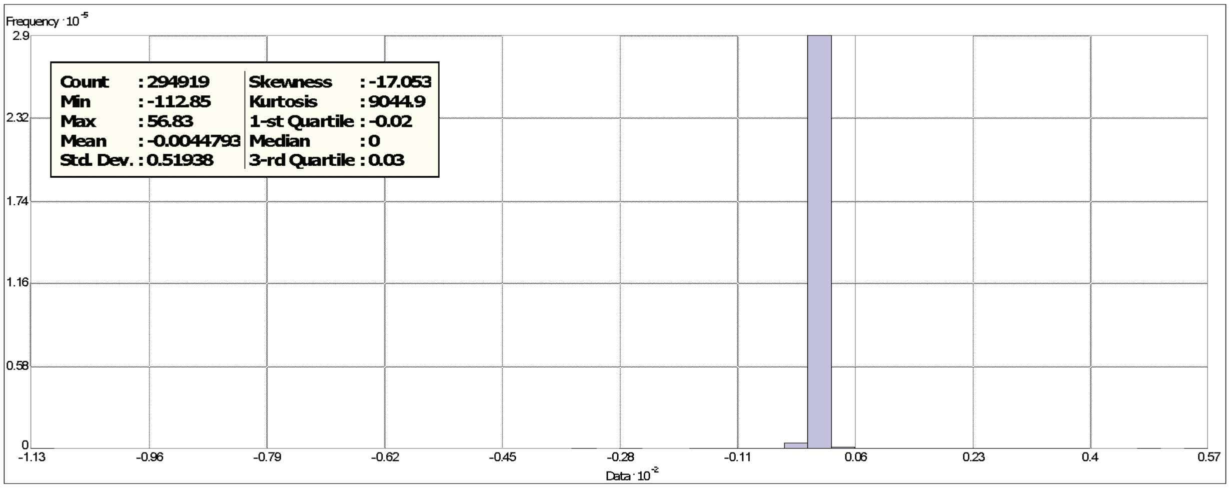

Figure 27. Histogram of the differences between NOS hydrographic data points and the Crescent City DEM NAVD 88 DEM.

4. Summary and Conclusions

Two integrated bathymetric–topographic digital elevation models of the Crescent City, California region, with cell sizes of 1/3 arc-second, were developed for the Pacific Marine Environmental Laboratory (PMEL), NOAA Center for Tsunami Research. The best available digital data from U.S. federal, state, local, and academic agencies were obtained by NGDC, shifted to common horizontal and vertical datums, and evaluated and edited before DEM generation. The data were quality checked, processed and gridded using ESRI *ArcGIS*, ESRI *ArcGIS World Imagery 2-D*, *FME*, *Fledermaus*, *GMT*, *MB-System*, *QT Modeler*, and *VDatum* software.

Recommendations to improve the Crescent City DEM, based on NGDC's research and analysis, are listed below:

- Conduct high-resolution bathymetric surveys adjacent to the Oregon Coast.
- Conduct topographic lidar surveys along the California Coast.

5. Acknowledgments

The creation of the Crescent City DEM was funded by the NOAA Pacific Marine Environmental Laboratory. The authors thank Nazila Merati, Marie Eble, and Vasily Titov (PMEL); Brian Hadley (CSC); Brooke McMahon (NOS); and Robert Yang (U.S. Army Corps of Engineers).

6. References

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Electronic Navigational Chart #18603, 16th Edition, 2002. St. George Reef and Crescent City Harbor. Scale 1:196,984. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Lim, E., L.A. Taylor, B.W. Eakins, K.S. Carignan, R.R. Warnken, P.R. Medley. Digital Elevation Model of Portland, Maine: Procedures, Data Sources and Analysis. 2009. NOAA Technical Memoradum NESDIS NGDC-30.

Myrick, G.B. and J. A. Melby, 2005. Monitoring of Dolos Armor Units at Crescent City, California, Coastal and Hydraulics Laboratory ERDC/CHL TR-05-10.

7. Data Processing Software

ArcGIS v. 9.3.1 – developed and licensed by ESRI, Redlands, California, http://www.esri.com/.

ESRI World Imagery (ESRI_Imagery_World_2D) – ESRI ArcGIS Resource Centers http://resources.esri.com/arcgisonlineservices/.

FME 2009 GB – Feature Manipulation Engine, developed and licensed by Safe Software, Vancouver, BC, Canada, http://www.safe.com/.

Fledermaus v. 7.0.0 – developed and licensed by Interactive Visualization Systems (IVS 3D), Fredericton, New Brunswick, Canada, http://www.ivs3d.com/products/fledermaus/.

GEODAS v. 5 – Geophysical Data System, free software developed and maintained by Dan Metzger, NOAA National Geophysical Data Center, http://www.ngdc.noaa.gov/mgg/geodas/.

GMT v. 4.3.4 – Generic Mapping Tools, free software developed and maintained by Paul Wessel and Walter Smith, funded by the National Science Foundation, http://gmt.soest.hawaii.edu/

MB-System v. 5.1.0 – free software developed and maintained by David W. Caress and Dale N. Chayes, funded by the National Science Foundation, http://www.ldeo.columbia.edu/res/pi/MB-System/.

Quick Terrain Modeler v. 7.0.0 – LiDAR processing software developed by John Hopkins University's Applied Physics Laboratory (APL) and maintained and licensed by Applied Imagery, http://www.appliedimagery.com/

VDatum Transformation Tool, California - Oregon California from Punta Gorda to Cape Blanco, v. 01 – developed and maintained by NOAA's National Geodetic Survey (NGS), Office of Coast Survey (OCS), and Center for Operational Oceanographic Products and Services (CO-OPS), http://vdatum.noaa.gov/.